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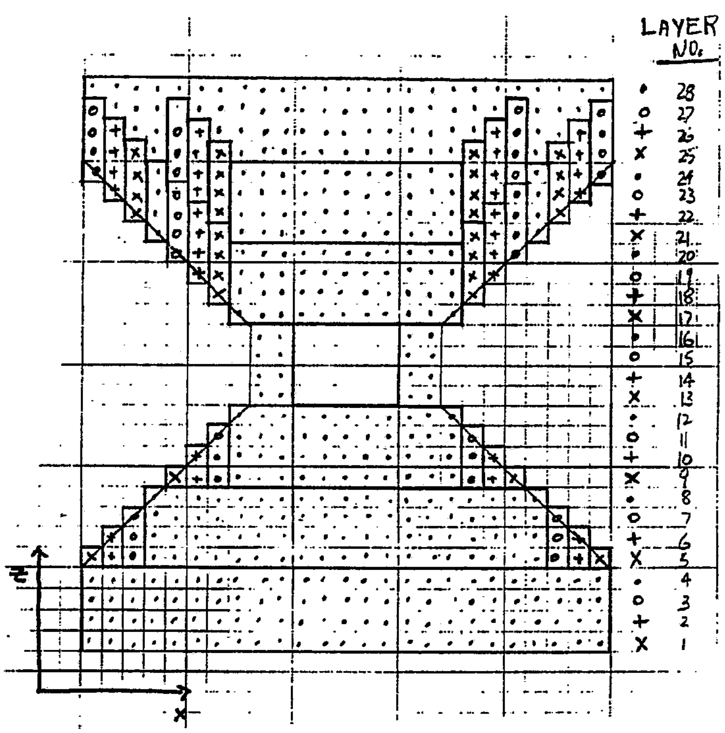
(54) Title: LAYER COMPARISON TECHNIQUES IN STEREOLITHOGRAPHY

(57) Abstract

A method of and apparatus for slicing a three-dimensional object representation into a plurality of layer representations. The layer representations are subsequently used to form the object layer-by-layer from a solidifiable material by stereolithography (711). If not already provided in the object representation, a plurality of layer boundary representations are first formed, and then the boolean difference (17), of successive layer boundary representations are computed to derive boundaries of up and down-facing regions, enabling different cure parameters to be specified for these different regions. In another method, the depth of the curable material within the objet underlying a selected area element is determined and compared to the depht to the minimum solidification depth of the material. The area element is exposed to solidifying synergistic stimulation only if the depth of the material equals or exceeds the minimum solidification depth. A next layer is created over the first layer without curing the first layer, if the depth is less than the minimum solidification depth. Another method and apparatus (714) eliminates or substantially reduces curling effects in stereolithographically formed objects. Synergistic stimulation is applied to a curable material to form a three-dimensional object through the build up of successive layers.



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Layer Comparison Techniques in Stereolithography

Technical Field of the Invention

This invention relates generally to the slicing of a three-dimensional object representation into layer representations for subsequent use in the stepwise layer-by-layer formation of the three-dimensional object through application of the principles of stereolithography, and more specifically, to the slicing of the object representation into the layer representations utilizing boolean comparisons between the borders of successive layers. In addition this invention relates to improved methods and systems for manufacturing parts (objects) more reliably, accurately (less curl and post cure distortion), and with increased surface resolution.

Background Art

Several building techniques have recently become available for building three-dimensional objects in layers. One such technique is stereolithography, which is described in U.S. Patent No. 4,575,330 (hereinafter the '330 patent), the disclosures of which is hereby fully incorporated by reference herein as though set forth in full. According to the principles of stereolithography, a three-dimensional object is formed layer-by-layer in a stepwise fashion out of a material capable of physical transformation upon exposure to synergistic stimulation. In one embodiment of stereolithography, layers of untransformed material such as liquid photopolymer are successively formed at the working surface of a volume of the liquid photopolymer contained in a container.

These layers are then selectively exposed to the synergistic stimulation to form successive object cross-sections. Moreover, upon transformation into the object cross-sections, the transformed material typically adheres to the previously-formed cross-sections through the natural adhesive properties of the photopolymer upon solidification. Additional details about stereolithog-

raphy are available in the following publications, all of which are hereby fully incorporated by reference herein as though set forth in full:

Publications

PCT Pub. # WO 89/10256
PCT Pub. # WO 89/10249
PCT Pub. # WO 89/10254
PCT Pub. # WO 89/10259
PCT Pub. # WO 89/11085
PCT Pub. # WO 89/11085
PCT Pub. # WO 89/10801
EPO Pub. # 86/171069
JP Pub. # 62-3596
PCT Pub. # WO 90/03255
PCT Pub. # WO 90/15674
PCT Pub. # WO 91/06378
JP Pat. App. # 291647/1990

As described in PCT Publication No. WO 89/10256, a stereolithography system will typically form a three-dimensional object in accordance with a corresponding object representation, which representation may be formed in a CAD system or the like. Before such a representation can be used, however, it must be sliced into a plurality of layer representations. The stereolithography system will then, in the course of building up the object in a stepwise layer-by-layer buildup, selectively expose the untransformed layers of material in accordance with the layer representations to form the object layers, and thus, the object itself.

Previous methods of forming the layer representations suffered from a number of disadvantages, however.

A problem with these methods is that it is difficult to utilize techniques for achieving enhanced surface resolution. This is because some effective methods and techniques of enhanced surface resolution inherently involve the comparison of cross-sectional information between two or more layers. Without a generalized layer

comparison capability, the required comparisons (for the referenced applications) must be separately developed for each particular case and for each particular operation that will be performed.

For photopolymer based systems an additional problem is that many photopolymers have a "minimum solidifiable thickness," i.e., a minimum thickness below which they cannot be sufficiently cured to form unsupported regions of transformed, cohesive material. For example, with presently preferred fluid photopolymers, if an attempt is made to try to form a feature of an object having a thickness less than the minimum solidifiable depth (MSD) or thickness, that feature will either simply fail to sufficiently solidify to become part of the object, or it will slump (i.e., fail to hold its shape). The minimum solidifiable thickness of a building medium (e.g., photopolymer) is not only a characteristic of the building medium or material itself but it also depends on the synergistic stimulation chosen and the environmental conditions surrounding the material. For example, oxygen absorbed in a photopolymer can act as a reaction inhibitor. Therefore, as used herein, "MSD" refers to the minimum solidification depth obtainable with a given material/solidification environment combination.

Since the MSD is the minimum solidification depth for forming unsupported regions of layers (i.e., down-facing features of the object), these regions must be given a cure depth of at least the MSD regardless of the thickness between individual layers or cross-sections from which the object is being formed. Therefore, due to the layer by layer formation process, even if the layers being used are thinner than the MSD, the accuracy of the stereolithographically reproduced object is limited by the MSD of the material being used.

As described in WO 89/10801, objects made using stereolithography tend to distort when the materials used change density between the untransformed state (e.g.,

liquid state) and the transformed state (e.g., solid state). This density change causes material shrinkage or expansion generating stress in a part as it is formed such that lower layers or adjacent structures tend to "curl" giving an overall distortion of the part.

Methods and apparatus have been developed to reduce curl which utilize creative stereolithographic building techniques. These building methods include, but are not limited to three concepts or techniques known as the brick and mortar technique (sometimes called tiling), the multi-pass technique, and the riveting technique.

Although these three techniques successfully and effectively reduce stress and curl, it must be recognized that, in general, each given application involves a trade-off between structural strength and curl. That is, the higher the structural strength required for a particular application, the more curling that will occur between layers.

Fig. 55 illustrates a side view of a spherical object 1 which is formed by the stepwise layer by layer buildup of stereolithography. The layers of the object are identified by numerals 1a, 1b, and 1c, respectively. In Fig. 55, the object representation 2 is depicted to be a representation of the surface of the object, and it appears as a circular envelope around formed object 1. The formed object 1 is depicted by the hatched area. Also shown are stair step surface discontinuities 3a through 3x which comprise deviations between the object 1 and the object representation 2. These surfaces discontinuities inherently form in objects produced through stereolithography, and result from the layers being used to form such objects having finite thicknesses. If infinitesimally small thin layers could be utilized, the surface discontinuities would be eliminated entirely. However thin layers may, in general, not be a feasible solution for reducing the surface discontinuities, and other techniques must be employed.

Several techniques have been proposed to eliminate surface discontinuities. Each one has one or more attendant problems, which prevent it from having universal applicability over a wide range of part geometries.

It is an object of the present invention to provide an improved slicing apparatus and method.

It is an object of the invention to overcome the MSD limitation by providing a method and apparatus of practicing high resolution stereolithography when using a fluid-like building material that is inherently incapable of making unsupported thicknesses of solidified material as thin as the desired accuracy when solidified by the chosen synergistic stimulation.

It is an object of the present invention is to provide an apparatus for and method of reducing surface discontinuities in a three-dimensional object formed by stereolithography, and to provide such an apparatus and method which can be implemented on the same apparatus used to build the object in the first instance, which does not require further equipment, and which is capable of being automated.

Additional objects and advantages will be set forth in the description which follows or will be apparent to those of ordinary skill in the art who practice the invention.

Disclosure of the Invention

To achieve the foregoing objects, and in accordance with a first aspect of the invention as embodied and broadly described herein, there is provided an apparatus for and methods of slicing a three-dimensional object representation into a plurality of layer representations, comprising the steps of: overlaying the object representation with a plurality of slicing planes spaced along a slicing dimension, wherein any two successive slicing planes of the plurality bounds a layer of the object representation, the bounded layers also being

successively spaced along the slicing dimension; associating each bounded layer of the object representation with the two successive slicing planes bounding the layer, the two successive planes comprising first and second slicing planes, the first slicing plane being situated lower along the slicing dimension than the second slicing plane; forming intersection segments for each bounded layer of the object representation comprising intersections between the object representation and a first selected one of the first and second slicing planes bounding the layer; forming projection segments for each bounded layer of the object representation comprising projections, onto a second selected one of the first and second slicing planes bounding the layer, of intersections between the object representation and a third selected one of the first and second slicing planes bounding the layer, which is different from the second selected one; forming a layer boundary representation for each bounded layer of the object representation comprising a boolean union of the intersection segments and the projection segments for that bounded layer; and introducing the layer boundary representation for each bounded layer into the layer representation for that layer.

The invention allows materials which are not considered capable of producing high resolution objects by stereolithographic methods to be used to create many of these high resolution objects through improved stereolithographic techniques. In terms of photopolymers, these heretofore non-high resolution photopolymers typically have absorption and solidification properties which make them incapable of being converted to a cohesive solid plastic of thickness less than some amount (e.g., 1 mm). In the practice of the present invention deviations are made from the typical approach, wherein these deviations involve leaving untransformed material on at least one portion of one cross-section, at least until after that cross-section has been coated over with untransformed

material in preparation for formation of an additional layer of the object, and wherein the portion(s) will be solidified by transformation of material after the formation of the coating.

The present method leads to more accurate creation of objects than is possible by use of typical stereolithographic techniques. Not all material to be solidified in a given area of a cross-section is necessarily solidified on that cross-section. It may be solidified through and simultaneously with a higher cross-section or layer, i.e., with the solidifying radiation penetrating downward through higher layers into the appropriate region.

The invention also contemplates a method for making the surface of an object built with a particular layer thickness (for the bulk of the object) appear as if it were constructed from finer layers. In addition, the instant method relates to not only making the surface appear more continuous (i.e., finer layers) but also building the bulk of the object with thick layers at the same time while maintaining the overall accuracy associated with finer layers.

Typically, in stereolithography, objects are built on webs or supporting structures. With the present method, the selection and placement of support structures should be carefully considered. Because of the possibility of staggering the formation of various regions of an initial cross-section to different layers, support placement is critical. Supports should be designed and placed to catch the regions that will be locally cured in association with the lowest layers.

Accordingly, it is an object of the present invention to provide a method and apparatus for curing at least two layers of a three-dimensional object, one as a balancing layer and the other as a balanced layer, of an object in relation to each other to reduce curling. This is accomplished by curing the balanced layer and then curing the balancing layer in relation to the balanced layer such

that reverse curl of the balanced layer caused by the balancing layer substantially offsets or negates normal curl of the balanced layer caused by the balancing layer. This method and apparatus is therefore applicable to balancing curl in all directions of curl such as when an object is built from the formation of successive layers from below or alongside previously formed layers.

For ease of disclosure this application is divided into four sections:

Section 1 is entitled "Boolean Layer Comparison Slice." This section describes the use of boolean operations in determining which portions of each layer continue from the previous layer through the present layer and through the next successive layer and which portions are up-facing or down-facing or both. Therefore, this section describes methods and apparatus for comparing initial data associated with each layer, and comparing such data between layers to form resulting data that will be used in the process of physically reproducing the object. Additionally, this section describes the use of such operations to yield appropriately sized objects (e.g., undersized or oversized) Utility of the concepts of this section to implementing and enhancing the teachings of the other sections will become apparent.

Section 2 is entitled "Simultaneous Multiple Layer Curing in Stereolithography." This section describes methods and apparatus for building high resolution objects from traditionally low-resolution combinations of building materials and synergistic stimulation, which combinations result in a minimum effective cure depth which is typically too deep to form the thin layers required for high resolution objects. This objective is accomplished by delaying the exposure of those areas on a particular cross-section that would negatively impact resolution if those areas were immediately cured upon formation of the cross-section. Resolution may be negatively impacted, for example, if, because of the cure depth involved, material

below this cross-section is inadvertently cured upon exposure of these areas. Therefore, to preserve resolution, exposure of these areas is delayed, and corresponding areas which are above these areas on higher cross-sections are exposed such that the cure depth is deep enough to cure the desired areas without inadvertently curing material on lower cross-sections.

Section 3 is entitled "Curl Balancing." This section discloses a method and apparatus for reducing curl distortion by balancing normal curl with reverse curl. This section discloses use of non-traditional cure depth and layer (or portion thereof) forming order to minimize curl distortion.

Section 4 is entitled "Improved Surface Resolution in Three-Dimensional Objects by Inclusion of Thin Fill Layers." This section describes methods and apparatus for forming high resolution objects by filling the surface discontinuities inherent in stereolithographically formed three-dimensional objects formed with thin fill layers of cured material during the layer by layer formation process.

As will be apparent to those of skill in the art, after reviewing the disclosure of this application, the teachings of these four sections can be combined in a plurality of ways in order to achieve favorable results. Several of these favorable combinations are discussed herein; however, many more are possible. Therefore, it is not intended that the teachings in any section apply only to that section but instead that they be viewed in light of the disclosure as a whole.

BRIEF DESCRIPTION OF THE DRAWINGS

Figs. 1 and 2 illustrate the use of the MSA in generating near-flat skin;

Figs. 3a and 3b are a flowchart of a first embodiment of the subject invention;

Fig. 4 illustrates the correspondence between slicing planes and cross-sections.

Fig. 5 illustrates the classification of triangles;

Fig. 6 illustrates the generation of projection regions;

Fig. 7 illustrates the relationships between S[i]+, S[i]*, and S[i+1]-;

Fig. 8 illustrates the formation of U[i] from L'[i] and L'[i+1];

Fig. 9 illustrates the overlap between up and down-facing regions;

Figs. 10 and 11 illustrate adjustments to up- and down-facing borders to prevent over-exposure;

Figs. 12a and 12b illustrate the detection of an area too small to benefit from the generation of skin vectors;

Fig. 13 is a flowchart of the method of implementing the first embodiment;

Fig. 14 is a flowchart of the detailed substeps of the method of Fig. 13;

Figs. 15a and 15b illustrate the process of splitting segments at intersection points;

Fig. 16 illustrates the process of assigning orientations to segments;

Figs. 17a and 17b illustrate the process of assigning orientations to horizontal segments;

Figs. 18a and 18b illustrate the concept of bigons as representing two overlapping segments;

Figs. 19a and 19b illustrate the case of three overlapping segments;

Figs. 20a and 20b illustrate the implementation of the boolean union operation;

Figs. 21a and 21b illustrate the treatment of bigons in the union operation;

Figs. 22a and 22b illustrate the implementation of line width compensation;

Figs. 23a-23c illustrate the implementation of the boolean differing operation;

Figs. 24a and 24b illustrate skin vector generation;

Figs. 25a-25c illustrate the generation of phantom borders for skin retraction;

Figs. 26a-26d and 27a-27d illustrate the clipping of phantom borders at corners;

Figs. 28a-28d is a flowchart of a second embodiment of the subject invention;

Figs. 29a-29d illustrate the use of an undersized building style with the subject invention;

Figs. 30a-30f illustrate an embodiment of cure width compensated to be utilized in conjunction with the subject invention;

Fig. 31 is a schematic side view of an object or part that can be built using stereolithography;

Fig. 32 is a side view of the object of Fig. 31 sliced using 10 mil cross-sections and constructed using a material that can form 10 mil thicknesses;

Fig. 32 is a side view of the object of Fig. 31 but this time sliced using 40 mil (1 mm) cross-sections along with a material cured to a 40 mil depth.

Fig. 34 is a side view of the object of Fig. 31 sliced using 10 mil cross-sections but constructed using a material that cannot form unsupported layers less than 40 mils in thickness (i.e., a 40 mil MSD material) using a typical stereolithography approach.

Fig. 35 is a side view of the object of Fig. 31 sliced using 10 mil cross-sections but constructed using a material that cannot form unsupported layers less than 40 mils (MSD) in thickness using a first embodiment of this invention.

Fig. 36 is a side view of the object of Fig. 31 sliced using 10 mil cross-sections but constructed using a material that cannot form unsupported layers less than 40 mils in thickness using a second embodiment of the invention.

Figs. 37-1 through 37-28 show horizontal views of layers 1-28 used to build the object of Fig. 32.

Figs. 38-1 through 38-28 show horizontal views of layers 1-28 used to build the object of Fig. 35. Phantom lines in the Figs. indicate region(s) at which no curing occurs on the layer of the region(s). Shaded lines indicate curing.

Figs. 39-1 through 39-28 show horizontal views of layers 1-28 used to build the object of Fig. 36.

Fig. 40 is a side view of a second object that can be built using stereolithography.

Fig. 41 is a side view of the object of Fig. 40 showing the slices and reproduction of the object by stereolithography using a high resolution material (MSD Layer thickness).

Fig. 42 is a side view of the object of Fig. 40 but now showing the portions that can be built (and the slice planes) with high resolution while using a material that has an MSD 4 times greater than the layer thickness. Also shown are the corner tip portions that require special handling.

Figs. 43a-3 show the object of Fig. 40 emphasizing several of the various ways that the sections (corner portions) thinner than the MSD can be handled to minimize inaccuracies or to maximize aesthetic appeal.

Figs. 44-1 through 44-21 are schematic illustrations of cross-sectional information (compressed along the Y axis) obtained by the application of "Slice Style 1" to the object depicted in Fig. 40 to produce the object of Fig. 41.

Figs. 45 and 46 are flow charts illustrating the basic system of the present invention for generating three-dimensional objects by means of stereolithography.

Fig. 47 illustrates a side view of two adjacent layers formed using standard stereolithographic techniques.

Fig. 47a illustrates a side view of a balanced layer and a balancing layer stereolithographically formed using a curl balancing technique.

Fig. 48 illustrates a three dimensional object formed using a curl balancing technique.

Fig. 49 illustrates a front view of the three-dimensional object shown in Fig. 48.

Figs. 49a through 49d illustrate a variety of cure depths used when transforming or curing the balancing layer and balanced layer of the object shown in Figs. 48 and 49.

Fig. 50 illustrates an object having a layer that has a balanced layer portion, a balancing layer portion, and a standard formation portion.

Fig. 51 illustrates a front view of the object of Fig. 49 containing a greater number of building layers and using a three-layer embodiment of curl balancing.

Figs. 51a through 51c illustrate various combinations for transforming a balanced layer relative to a balancing layer in a three-layer embodiment such as illustrated in Fig. 51.

Fig. 52 illustrates a front view of the object of Fig. 49 containing a greater number of building layers and using a four-layer embodiment of curl balancing.

Figs. 53 and 54 illustrate top views of three lines of material on a single layer which utilize curl balancing techniques.

Fig. 55 illustrates a three-dimensional object built using an undersize style;

Figs. 56a through 56d illustrate various methods of filling surface discontinuities at down-facing features with fill layers;

Figs. 57a through 57d illustrate various methods of filling surface discontinuities at up-facing features with fill layers;

Figs. 58a and 58b compare the surface resolution obtainable by two different fill layer thicknesses;

Figs. 59a, 59b and 59c depict various non-uniform filling techniques that may be used for filling in surface discontinuities;

Figs. 60a, 60b and 60c provide a three-dimensional illustration of the fill layers of the subject invention;

Figs. 61a through 61j depict several possible transition regions for a slanted down- facing region;

Figs. 62a through 62d depict the transition regions of Fig. 61a as reproduced in the three-dimensional object;

Figs. 63a through 63d depict the transition region of Fig. 61b as reproduced in the three-dimensional object;

Figs. 64a through 64d depict the transition region of Fig. 61c as reproduced in the three-dimensional object;

Figs. 65a through 65d depict the transition region of Fig. 61d as reproduced in the three-dimensional object;

Figs. 66 through 69 are counterparts to Figs. 62 through 65, but for up-facing slanted surfaces instead of for down-facing slanted surfaces;

Figs. 70a through 70d depict the transition region of Fig. 61i as reproduced in the three-dimensional object;

Figs. 71a through 71d depict the transition region of Fig. 61j, as reproduced in the three-dimensional object;

Figs. 72 through 75 depict examples of implementations of the subject invention;

Figs. 76a through 76c and 77a through 77f illustrate embodiments of the subject invention employing menisci to smooth over surface discontinuities; and

Fig. 78 illustrates the smoothing effect of the meniscus.

Best Modes for Carrying Out the Invention

Section 1: Boolean Layer Comparison Slice

An overview of a first embodiment of the subject invention will now be provided. This embodiment normally builds oversized parts, but provides the capability of rapidly and flexibly building undersized parts, or average-sized parts. Moreover, this embodiment still requires that the object representation be converted into the intermediate format of tesselated triangles. However,

as will be seen in the following discussions, this embodiment is still much less dependent on the triangular representation then previous slicing methods, enabling it to be used with other data formats with simple modifications. These simple modifications will also be pointed out in the following description. Also, if a tesselated triangle representation is input to this embodiment of the invention, this embodiment will round all triangle vertices to slicing layers. Rounding of triangle vertices is described in WO 89/10256. Rounding actually preserves object features which would otherwise be lost by the slicing process. Therefore, since the enhancement to object resolution resulting from preserving object features is believed to outweigh the detrimental impact that rounding may have on resolution, rounding of vertices is performed in this embodiment.

Alternative embodiments can use non-rounded vertices if appropriate care is taken to deal with cases where features terminate between layers.

An overall flowchart for the method of the first embodiment is illustrated in Fig. 3a and 3b. The first step is step 10, wherein the triangular representation is overlayed with a plurality of slicing layers z[i], spaced along a z-axis. This is conceptually shown in Fig. 4, which shows object representation 25 interlaced with slicing layers z[1]-z[6] spaced along the z--axis.

Turning back to Fig. 3a, in step 11, each of the tesselated triangles of the object representation intersecting a slicing layer is then classified into "+" triangles, "-" triangles, or "neither" triangles. For a slicing plane z[i], "+" triangles are defined as those triangles which pass through the slicing plane extending upwards, or which begin at the slicing plane and extend upwards; "-" triangles are those triangles which pass through the slicing plane extending downwards, or which end at the slicing plane and extend downwards; if a triangle is neither a "+" or a "-" triangle, it falls into

the "neither" category. Many triangles are both "+" and "-" triangles.

Turning to Fig. 5, for example, triangles 26a-26h are shown, all of which intersect slicing plane z[i] at one or more points.

Triangle 26a will neither classify as a + or a - triangle, since it is entirely within the slicing plane and does not extend above or below it. It is therefore a "neither" triangle. Triangles 26b and 26c are both + triangles, since both begin at the slicing layer, at a line segment and a point, respectively, and extend upwards. Triangle 26f is both a "+" and a "-" triangle since it fits the definition of both categories: it is a "+" triangle since it passes upwards through the slicing plane (intersecting it at a line segment), and it is a "-" triangle since it also passes downwards through the slicing plane. Triangles 26g and 26h are both "-" triangles since both end at the slicing plane, at a line segment and a point, respectively, and extend downwards.

Turning back to Fig. 3a, in step 12, for each slicing plane z[i], the method will form a border, known as S[i]+, from the intersections between the "+" triangles and the slicing plane. The process of forming a border from the intersections between triangles and planes, such as slicing planes (sometime known as slicing layers) and the like, is described in detail in WO 89/10256.

In step 13, for each slicing plane z[i], the algorithm will also form a border, known as S[i]-, from the intersections between the "-" triangles and the slicing planes.

In step 14, for each slicing plane z[i], the algorithm will determine the projection of all triangle areas between z[i] and z[i+1] onto z[i]. The projection is defined as S[i]*. Turning to Fig. 6, this figure shows triangle 27, which is one of the triangles situated between slicing planes z[i] and z[i+1]. As shown, the projection of triangle 27 onto slicing plane z[i] is

identified with reference numeral 28. Once the projections are determined, the boundaries of the projection will be determined in a manner analogous to the generation of near-flat boundaries described in detail in WO 89/10256, which are also determined from triangular projections. These boundaries are known as S[i]*.

Note that each object cross-section, CR[i], which is planned to be formed, corresponds with the data between two successive slicing planes z[i] and z[i+1]. This correspondence will guarantee that the correct number of cross-sections, which should equal the number of slicing planes minus one, is formed.

Turning back to Fig. 3a, in step 15, for each cross-section, CR[i], layer boundary data, L[i], is formed, by taking the boolean union of S[i]+, S[i]*, and S[i+1]-. Turning to Fig. 7, which is top view of the plane 9 from Fig. 4, the generation of L[4] is shown. First, S[4]+, S[5]-, and S[4]* are generated, as shown, and then the union of these three areas is taken to determine L[4], as shown. If the above-described downshift is to be avoided, then the above data should be associated with CR[i+1] since it is used to form the portion of the object between z[i+1] and z[i].

Note that step 15 creates a layer boundary which is always oversized compared to the original object representation. In Fig. 7, for example, the most accurate representation of the object at slicing plane z[4] is actually S[4]+, which is smaller than L[4]. Therefore, the final object, once built, will be oversized compared to the object representation. The generation of undersized and average sized objects in this first embodiment will be described later on.

Turning back to Fig. 3a, in step 16, line width compensation ("LWC") is performed, according to which the layer boundaries L[i], generated in step 15, are compensated for one to the finite cure width of the material after it transforms. Essentially, in this step, the layer

boundaries are displaced inwards (towards the solid region which is being bounded) by about one-half of the cure width associated with the appropriate cure depth, so that when the beam of synergistic stimulation is directed to trace the object boundaries, and material at the boundary is transformed, the object will be the correct size. If LWC were not performed, the xy dimensions of the object would be oversized by about one cure width. LWC is explained in more detail further on. Performing LWC at this stage of processing implicitly assumes that the various types of boundaries that will be formed at later stages of the processing can all be adequately compensated by this single adjustment. Alternatively, it is possible to do additional compensating for one or more of the boundary types at a later stage. This additional compensation can be either of a positive or negative nature.

The amount of offset for the layer boundary is known as the layer boundary offset (LBO). The amount of offset is not simply one-half the beam width, but instead is one-half the cure width, which is the width of transformed material after exposure to the beam. In general, the cure width will be different from the beam width, since the cure width is dependent on cure depth, as explained in detail in WO 89/10256. That is, as the cure depth increases, so does the cure width.

Therefore, the LBO may be different from layer to layer, since the layer thickness, and hence cure depth, may vary from layer to layer. The LBO for layer i is designated as LBO[i].

To determine the LBO for a particular layer, the desired layer thickness is first determined (determined from the difference between successive slice planes z[i] to z[i+1] or the like) and the overcure amount, typically 6 mils, is then added. The result is the expected cure depth for the layer. As described in WO 89/10256, the overcure amount is the designated amount by which one layer is designated to penetrate into, and therefore

overlap, the layer below it in order to ensure good adhesion between the layers. Once the cure depth for the layer has been determined, the program will then determine the estimated cure width based on the cure depth, and set the LBO to one-half that amount. Optionally, the down-facing regions, which will be later determined for layer i, can be given a slight negative compensation (their areas will grow) to compensate for any decrease in cure width due to a somewhat smaller cure depth.

To estimate the cure width, a plurality of previously determined data pairs may be utilized, each pair comprising an empirically measured cure depth and its corresponding cure width. Assuming that the expected cure depth does not fall exactly on one of the cure depths in the data pairs, the cure width will be estimated simply by interpolating. Alternatively, cure depths and widths can be determined from beam profile data and known properties of the building material.

Once the LBO has been determined, the layer boundaries are adjusted by this value. The compensated layer boundaries are designated as L[i]'.

In step 17, the process of generating up-facing boundaries for each layer is performed. To begin the process for each layer, the boolean subtraction between that layer and a successive higher layer is performed, which essentially determines the area on the layer which is not overlapped by the successive higher layer. The non-overlapping areas are designated as U[i].

To perform the boolean subtraction, utilization is made of a mathematical identity which results in computational efficiency. As is known, the boolean subtraction between two areas, A and B, is equal to the intersection between area A and the complement of area B:

$$A-B = A\cap(-B)$$

Therefore, to perform the boolean subtraction referred to earlier, the following computation is performed in step 17:

$$U[i] = L[i]' - L[i+1]' = L[i]' \cap (-L[i+1]')$$

As an example of this computation, Fig. 8 shows the derivation of U[4] from L[4]' and L[5]', which are taken from the example of Fig. 4. U[4] is the shaded area in Fig. 8. The complement of L'[5] is everything but the area enclosed by L'[5]. Therefore, the intersection between this complement and L'[4] is the area enclosed by L'[4] excluding that portion that is also enclosed by L'[5].

Note that U[4] represents only the first step in the determination of the up-facing areas. This is because the areas defined by U[i] might actually include down-facing areas as well as up-facing areas. Therefore, an adjustment needs to be made to U[i] to exclude down-facing areas. (As mentioned previously, it is important to distinguish down-facing areas from all other areas since they will generally not be overcured.)

Fig. 9 shows an example where the area designated by numeral 29 would be included in U[i], but which should be excluded since it is also a down-facing region. This area is a down-facing region since L[i]' does not overlap L[i-1]', the next lower layer, in this region. As indicated earlier, the down-facing regions need to be excluded, since they do not overlap the next lower layer and should not be over-cured. The next two steps accomplish this. Alternatively, areas that are both up-facing and down-facing can be labeled as down-facing, as is done in this embodiment, or they may be given a different designation so that areas that are only down-facing can be cured differently from those that are both up-facing and down-facing.

Turning back to Fig. 3a, in step 18, the down-facing borders, D[i], are determined for each layer by taking the boolean difference between the compensated layer boundaries for that layer, L[i]', and the compensated layer boundaries for the previous layer boundary, L[i-1]'. In the manner indicated previously, this is accomplished by

taking the intersection between L[i]' and the complement of L[i-1]', according to the following formula:

$$D[i] = L[i]' - L[i-1]' = L[i]' \cap (-L[i-1]')$$

Next, in step 19, the up-facing boundaries computed in step 17, U[i], are compensated to subtract out any down-facing regions which may also be present in the up-facing regions. This is accomplished by taking, for each layer, the boolean difference between U[i] and D[i]. In the manner indicated previously, this difference is determined by taking the intersection between U[i] and the complement of D[i] as per the following formula, to compute the adjusted up-facing boundaries, U[i]':

$$U[i]' = U[i] - D[i] = U[i] \cap (-D[i])$$

Note that, at this point, the adjusted layer boundaries, L[i]', still encompass the up-facing and down-facing regions, D[i] and U[i]'. Therefore, these two areas need to be subtracted from the layer boundaries. This is accomplished in the next two steps in Fig. 3a.

In step 20, the layer boundaries are adjusted again to subtract out the down-facing regions. The twice-adjusted layer boundaries, L[i]", are computed by taking the boolean difference between the compensated layer boundaries, L[i]', and the down-facing boundaries, D[i]. In step 21, the layer boundaries are adjusted a third time to subtract out the up-facing regions. The thrice-adjusted layer boundaries, L[i]''', are computed by taking the boolean difference between the twice-adjusted layer boundaries, L[i]", and the adjusted up-facing boundaries, U[i]'. Note that, at this point, the following mutually exclusive, descriptive information has been computed for each cross-section: L'''[i], D[i], and U'[i].

Note that it is still desirable to separate out the up-facing boundaries from the layer boundaries and obtain mutually exclusive data even though up-facing regions will typically be cured with the same overcure as other regions within the layer boundaries. If the up-facing boundaries were allowed to remain within the layer boundaries, then

the areas within the layer boundaries would be redundantly defined. As a result, these areas may be traced more than once by the synergistic stimulation, and therefore overcured, resulting in possible distortion either through undesirable increases in the cure depth or the cure width at these areas.

Turning now to Figs. 11, 12a and 12b, some additional adjustments to the up-facing and down-facing boundaries must be made in order to avoid additional redundant definitions of certain areas, with the resultant possibility of over-exposure of these areas. Fig. 11 illustrates a top view of a layer of an object having an up-facing region 30. The thrice-adjusted layer boundary, L[i]''', is referenced with numeral 31, and the adjusted up-facing boundary, U[i]', is referenced with numeral 34. The areas encompassed by the layer boundary and the up-facing boundary meet, but do not overlap, along segment 32. However, if the entire area encompassed by area 30 is exposed to form a transformed area, which abuts right up against segment 32, and in addition, if the entire area enclosed by boundary 31 is transformed to form a transformed area which also abuts against 32, then the material along this segment will be exposed four separate times, i.e., through exposure of areas enclosed by 31 and 34, and through exposure of layer boundary 31, and up-facing boundary 34. As indicated previously, this over-exposure should be avoided in order to prevent the resultant increase in cure width and cure depth which results. Therefore, adjustments to the up-facing and down-facing borders are useful to prevent this over-exposure. This is accomplished in steps 22 and 23.

An additional and very important result of these adjustments is that they will have the beneficial effect of eliminating the generation of skin vectors for areas too small to actually require skin vectors. Turning to Fig. 12a, for example, the area identified by numeral 35 is assumed to represent either an up or down-facing region

which is too small to benefit from the generation of skin vectors. This is so because when the synergistic stimulation traces segments 35a and 35b around the perimeter of the area, this area will be automatically transformed (due to the cure width involved).

The determination of such areas can be accomplished, for example, by moving segment 35a to the right by one-half the cure width, while also moving segment 35b to the left by one-half the cure width, as shown. As will be discussed subsequently, these steps can be accomplished by utilizing, in large measure, the LWC algorithm from step 16. If the result of migrating these segments is the collapse of the region or partial collapse, then this indicates that skin vector generation need not be performed in this region or portion of this region. As shown in Fig. 12b, the migration of the segments collapses the region into line segment 36, indicating that skin vectors need not be generated. The detection of these areas is performed in the next two steps of Figs. 3a and 3b.

In step 22, an up boundary offset (UBO) is computed for each layer in a similar manner to the computation of the LBO, i.e., by interpolating based on the value of the layer thickness plus an expected overcure amount. This value is used to offset the up-facing boundaries in the manner very similar to that described previously. The primary difference between the use of the UBO and the LBO is that the UBO is not used to form physical boundaries that will be drawn, whereas the LBO is used to form such boundaries. The UBO is used to form boundaries from which the appropriate areas for skinning and/or hatching will be determined. As such, if these areas are reduced to zero or become negative, they are simply not skinned and/or hatched.

The LBO, on the other hand, is used to offset the boundaries that will physically be formed when producing a layer of a part. As such, when areas within these boundaries reduce to zero, or become negative after the

compensation associated with the LBO, a decision must be made as to whether or not it is appropriate to form the collapsed feature as a single line of cured material or whether it is more appropriate to simply remove such features from further consideration. The most preferred choice may vary from part to part or layer to layer or region of a layer to region of a layer. Therefore, the most appropriate method of making the decision may be to make it a user specified option. This decision may be made on a part by part basis, layer-by-layer basis, or a region of a layer by region of a layer basis. This difference between the use of the LBO and UBO leads to somewhat different processing routines as will be described later.

Next, the adjusted up-facing boundaries U[i]' are adjusted inwards by about one-half the UBO for that layer, UBO[i], to obtain the twice-adjusted up-facing boundaries, U[i]". Note that with the generation of U[i]", the singly adjusted up-facing boundaries U[i]', are still retained. This is because the twice-adjusted boundaries are only kept temporarily for the purpose of generating skin vectors and/or hatch vectors, and are not retained for the purpose of generating border vectors. Instead, the singly adjusted boundaries, U[i]', are kept for this purpose.

Then, in step 23, adjusted down-facing boundaries, D[i]', are computed by adjusting for a down-boundary offset, DBO, for that layer. The down boundary offset values for each layer are computed in a manner analogous to the offsets for the up boundaries in step 21 except for generally a smaller depth of cure and smaller corresponding width of cure, and the adjustment to the down-facing boundaries is made in a similar manner. Again, with the generation of the singly-adjusted boundaries, D[i]', the unadjusted boundaries, D[i], are still retained. This is because the adjusted boundaries are only used for the temporary purpose of generating skin vectors and/or hatch

vectors, the unadjusted down-facing boundaries, D[i], being retained for the generation of the border vectors.

Note it is also possible to determine and use an additional offset value to compensate the L'''[i] or the L''[i] boundaries to produce secondary boundaries. The secondary boundaries can then be used for the generation of crosshatch (hatch) or skin (if used), wherein the original L'''[i] or L''[i] would still be used to form the physical boundaries that would enclose the hatch or skin produced from the secondary boundaries.

Finally, in step 24, vectors are generated from the boundary data as follows. First, for each layer, layer boundary vectors (LB) are generated from the thrice adjusted layer boundaries L'''[i]. (This is a simple process and is simply the generation of one or more loops of vectors which trace out the boundaries.) Second, the flat up boundary (FUB) vectors are generated from the adjusted up boundaries U[i]'. Third, layer hatch (LH) vectors are generated from the twice adjusted (not thrice-adjusted) layer boundaries, L[i]", using one of the hatch generation algorithms to be described subsequently. Note that the twice-adjusted boundaries, L[i]", are used, which encompass the up-facing regions but not the down-facing regions (see step 21 in Fig. 3b), rather than the thrice-adjusted boundaries, L[i]'". This is because hatch vectors will eventually be generated for both the layer boundary and up boundary regions, and it is more efficient to generate them in one step, rather than in two steps, which would be required if L[i]''' were used here. Although generally found to be unnecessary, separate hatch vectors can be generated for the L'''[i] regions and for the U'[i] regions instead of a single set for the combined L'''[i] and U'[i] regions. This can be done at the cost of producing additional vectors but with the benefit of yielding additional versatility in the process of actually transforming the building material. Note that the generation of hatch vectors for the down-facing regions cannot be

combined with the generation of hatch vectors for the layer boundaries since these vectors for the down-facing regions will likely be given different cure depths and possibly completely different processing from that given to the LH, since a uniformly cured, non-over-cured region is desired to be formed. Fourth, the flat down boundary (FDB) vectors are then derived from the unadjusted down-facing boundaries, D[i], generally without any overcuring specified. Fifth, down hatch boundary vectors (NFDH) are formed from the down boundaries, D[i], using one of the hatch generation algorithms to be described subsequently. Sixth, the up fill vectors (FUF) are formed from the twice-adjusted up boundaries U[i]", and, then, the down fill vectors (FDF) are formed from the adjusted down boundaries, D[i]', using one of the skin vector generation algorithms described subsequently.

Note that the algorithm retains some of the vector mnemonics associated with the previous SLICE programs described in WO 89/10256 in order to retain compatibility with the remaining computer programs other than SLICE which run on the PROCESS computer. The correspondence between vector mnemonics, vector description, the borders used to generate the vectors, and the order in which each vector type is generated, and then drawn, is summarized below:

ORDER	MNEMONIC	DESCRIPTION	DERIVED FROM
1	LB	layer boundary	L'''[i]
2	FUB	up boundary	U'[i]
3	LH	layer hatch	L"[i]
4	FDB	down boundary	D[i]
5	NFDH	down hatch	D[i]
6	FUF	up fill	U"[i]
7	FDF	down fill	D'[i]

Although the above-listed drawing order is preferred, other satisfactory drawing orders may be utilized. An important aspect of selecting the drawing order is to avoid drawing vectors that are not adequately supported by

previously-formed portions of the object. If these unattached or loosely attached vectors are drawn prior to drawing other vectors, the transformed material forming the vectors can drift out of position or be distorted out of position before they can be adhered to other vectors. Therefore, it is usually advisable to solidify the material on a given layer in a manner which starts with the supported regions (since these regions will be adhered to the cross-section below) and then solidify the material which extends radially outward from these regions into the unsupported regions. This desired manner of formation can be implemented by comparison of adjacent cross-sections, known cure depths and widths for each vector, and known attributes of the drawing style used and of any curl reduction methods used. The above-described order reflects these considerations. Additionally, it always draws boundaries prior to their associated hatch or fill to ensure that the hatch and fill will be constrained by the boundaries even if the hatch and fill should initially be unadhered.

Another possible drawing order is LH, FUF, LB, FUB, FDB, NFDH, and finally FDF. This drawing order creates the LH and FUF before their corresponding boundaries since it can be assumed that both of these vector types are used to transform material which is supported from below by material which was transformed in association with the previous cross-section. Furthermore, this drawing order has the advantage that the boundaries will not be distorted by shrinkage of the hatch and fill as the hatch and fill are formed. Therefore, it may be assumed that the boundaries will ultimately be located in more accurate positions.

The above list of vector types does not contain an up-facing hatch category. As stated previously, this is because the up-facing hatch is included in the LH of the above list. This inclusion has generally been found to be satisfactory, but the up-facing hatch can be separated out

into its own category if the need or desire arises. Separating the LH into its own category is a specifiable option in the present software.

Implementation

The implementation of the above embodiment will now be described. Fig. 13 illustrates an overall view of the implementation, which comprises the steps of performing union operations to form boundaries in step 37, performing line width compensation in step 38, performing difference operations to form non-overlapping boundaries in step 39, and performing skin and hatch retraction and fill and/or hatch vector generation in step 40. All these steps are presently conducted on the SLICE computer (which may be the same as the PROCESS computer), which takes the tesselated triangle formatted object representation as input, and produces vectors as output. The PROCESS computer is one with or is coupled to the SLICE computer for receiving these vectors, and then, responsive to these vectors, directs the beam of synergistic stimulation to trace out the vectors on a working surface of the material.

Each of these steps will be addressed in order. The detailed substeps which make up step 37 are illustrated in Fig. 14.

First, in step 50, all the triangles are sorted by the minimum z-component of any of the triangle vertices. The z-axis is assumed to be the slicing axis, which in the first embodiment, is the vertical dimension. Therefore, this step will order the triangles along the slicing axis. It should be noted that the choice of the z-axis is arbitrary, and, assuming a cartesian coordinate system, the y or x-axis could equally have been used.

Then, in step 51, the triangles are overlayed with a plurality of slicing planes spaced along the z-axis. Then, after consideration of all the triangles between any two successive slicing planes, a segment list is generated, comprising segments generated from the intersections

of all such triangles with the one of the two successive slicing planes having the smaller z-component. In addition, a projection list is generated, comprising segments generated from the projections of triangles, between the two layers, onto the smaller z- component slicing plane, with flat and vertical triangles excluded from consideration. If it is desired not to shift the reproduced object along the z-axis, both these lists are associated with the higher of the two layers after their formation. After the segment and projection segment lists have been formed for a cross-section, segment and projection lists for all the cross-sections are formed. In each instance, the segment and projection lists for a cross-section are formed from the two slicing layers which bound the cross-section. Alternatively, all the segment lists may not be generated. Initially, it is possible to generate such segment lists for the preceding succeeding layer, the present layer, and the successive layer. After the appropriate computations are done for the present layer, the vectors for the present layer are stored or executed. The information for the succeeding layer is removed, followed by the layer designation being transferred upward so that was the next successive layer becomes the present layer. The process is then repeated, thereby minimizing memory and storage space usage.

Note that the segments in the projection list, upon formation, are ordered in a counter-clockwise orientation, such that in following the directions of the segments which bound a projection, the solid regions are to the left and the hollow regions are to the right of the boundary. Another way of expressing this is that the segments follow the right hand rule, whereby the segments are assumed to encircle solids in a counter-clockwise direction, and to encircle hollow regions in a clockwise orientation.

Unlike the segments in the projection list, however, the segments in the segment list are not oriented upon

formation. These segments are oriented in step 57, discussed subsequently.

For a given cross-section, beginning in step 52, the segment list is first operated on to clean it up, and correct for any corrupted input data. The inputted triangles are assumed to completely span the surface of the object, and to abut other triangles only at their vertices. If either or both of these assumptions are violated, the input data representing the triangles may be corrupted. This may manifest itself in the form of gaps or overlaps in the segment list. As discussed below, in step 52 and subsequent steps, these gaps are filled.

In step 52, the segments in the list are ordered according to their minimum y dimension, although the x-dimensions could equally have been used. Then, in step 53, the endpoints of segments are considered in turn by comparing them with the endpoints of successive segments, and if any two endpoints match, the corresponding segments are combined to form "polylines." In step 54, the endpoints of any polylines that have not closed upon themselves to form polygons are considered in turn, and compared with the endpoints of successive unclosed polylines. If gaps are present, segments are created to fill in the gaps, considering the shortest gaps first. The result is to form polygons out of the unclosed polylines. In the closing of polylines into polygons, precautions are taken to avoid vectors which cross over other vectors. At such intersection points, both vectors are split as necessary and non-overlapping polygons are formed or one polygon and a non-overlapping polyline is formed.

In step 55, after any gaps have been filled, the longest possible segments are reformed from the polygons by combining successive collinear or nearly collinear polylines or segments where possible. A characteristic of these longer segments, unlike those used to form the polygons earlier, is that all gaps will have now been removed, and the segments will completely form polygons.

Moreover, another characteristic of these longer segments is that they will not be allowed to pass over any other segment. This is accomplished by following the rule to split a segment into multiple segments at an intersection point, to avoid having any two segments cross or to have a segment pass through an intersection point with another segment.

The splitting process is illustrated in Figs. 15a and 15b. Fig. 15a shows segments 61 and 62 intersecting at point 63. To avoid violating the rule mentioned earlier, the segments are divided up into the four sub-segments A, B, C, and D.

Fig. 15b shows another example of splitting segments 64 and 65, which intersect at 66, except that here, the splitting is into three sub-segments, A, B, and C, rather than into four sub-segments.

Turning back to Fig. 14, in step 56, the reformed segments are ordered by their minimum y dimension.

In step 57, orientations are assigned to the segments, since, as discussed previously, unlike the segments in the projection list, these segments have not been assigned orientations. To do so, the segments are first intersected with so-called "infinity" lines (so-called because they are considered to originate at infinity), which are parallel to the x-axis (although the y- or z-axis is equally possible). Then, at each intersection point with a segment, a quantitative volume analysis ("QV analysis") is performed, and, as a result of this analysis, the segment is assigned a corresponding orientation.

To begin the QV analysis, it is assumed that an infinity line always begins in a hollow region, and that every time it intersects a segment, that it is either entering or exiting a solid region. The segments are assumed to be oriented so that to their left is solid and to their right is hollow, that is they are assumed to encircle a solid region by looping around it in a counter-clockwise orientation. This is equivalent to orienting

these segments according to a right-hand rule. Again, a left-hand rule is also possible.

The quantitative volume ("QV") associated with an infinity line will vary from one point on the line to another depending on whether that portion of the infinity line is located within a hollow portion, or a solid portion. When the infinity line is in a hollow region, it is assumed to have a QV of 0, and when it is within a solid region of an object, it is assumed to have a QV of 1 (if the infinity line were located within an overlapping solid region of two objects, it would have a QV of 2, and so on). This situation of overlapping solid regions is excluded from this stage of the processing since at this stage hollow and solid regions are being determined by alternating the designation as successive boundary vectors are determined. A different algorithm is possible that could substantially process overlapping solid regions at this phase.

Each segment can only have one orientation associated with it since over its entire length it, by definition and by virtue of the previously-described splitting technique, is bound by hollow on one side and by solid on the other.

The ordered segments are successively overlapped with infinity lines until each segment has been assigned an orientation. Any number of infinity lines can be used, the only provision being that enough be used so that each segment will be assigned an orientation. The first infinity line may be chosen to intersect as many segments as possible. After the orientations for these segments are assigned, another infinity line is intersected with as many remaining segments as possible, orientations are assigned, and the process repeats itself until all segments have been assigned orientations.

The above process can be illustrated with the aid of Fig. 16, which shows segments 67a-67f, and 68a-68g. These segments all have at least a component parallel to the y axis and they are assumed to be ordered by minimum y, and

are therefore illustrated accordingly. The y-axis is designated with numeral 71.

First, an infinity line, designated by numeral 69, is chosen to intersect as many segments as possible. In this case, this line overlays segments 67a-67c and 67e. The actual intersections of the segments with the line are designated as A, B, C, and D.

As mentioned earlier, the origin of the infinity line is assumed to be at infinity, which is assumed to be hollow. Therefore, the infinity line at infinity is assumed to have an associated quantitative value of 0. This is indicated on the infinity just prior to the intersection with segment 67a at point A. Next, each intersection point along the infinity line is considered in turn, and QV values are successively assigned to each portion of the infinity line after intersection with a segment. If the QV value makes a transition from 0 to 1, this indicates the entry of solid. If it makes a transition from 1 to 0, this indicates the exiting of solid. The successive QV values are as shown in the figure.

Next, assuming an orientation, which indicates solid to the left and hollow to the right, the orientations of the segments are derived from the QV values on the infinity line. If the QV value makes a transition from 0 to 1 across a segment, this indicates that a solid has been entered, and following the right-hand rule, it is assumed that the segment is pointing downwards. Of course, if the QV makes a transition from 1 to 0, this indicates that a solid has been exited, and following the right-hand rule, it is assumed that the segment is pointing upwards. If the segment is determined to point downwards, it will be given an orientation of 1, while if it is determined to point upwards, it will be given an orientation of -1. The derived orientations are shown in the figure, as numbers below the corresponding segments. An arrow has also been added to each segment to pictorially show its derived orientation.

Next, another infinity line is drawn, identified by numeral 70 in the figure, to intersect another group of segments, identified by numerals 68a-68f in the figure. The corresponding intersection points are identified as E, F, G, H, I, and J in the figure. Then, the above analysis is repeated, to assign orientations to the intersected segments, which are indicated in the figure.

A consistency check is then performed to determine if a segment assigned an orientation by two different infinity lines has been assigned the same orientation. In Fig. 16, for example, if segments 68a and 67a were part of the same overall segment (which situation is denoted by the broken line connecting these two segments) then a check would be made to ensure that the orientations assigned by the different infinity lines to this segment are the same. This is, in fact, the case in Fig. 16. Additional checks can be performed to ensure that segments in each polygon have been assigned compatible directions.

Several special cases will now be considered. The first is illustrated in Figs. 17a-17b, where the segment 72 to be assigned an orientation is horizontal to the infinity line 73. In this instance, it will be assumed that the infinity line passes through the segment from top to bottom, as shown by the broken line in the figures, even though in reality, the infinity line follows the path indicated by the solid line in the figures. If the QV changes from 0 to 1 as in Fig. 17a, the segment will be assigned an orientation of 1, while if the QV changes from 1 to 0, as in Fig. 17b, the segment will be assigned an orientation of -1.

Another special case is where two or more segments overlap. Overlapping segments may be caused by triangles overlapping. This situation may occur as triangle vertices are rounded to slicing layers.

To handle this situation, an orientation value will be assigned to the overlapping segments as a whole. This value is equal to the sum of the orientations of the

individual segments. In addition, a new value, a "biorientation" value, is assigned both to the individual segments and to the overlapping segment groupings. For individual segments, the biorientation value is set to 1. For segment groupings, the biorientation value will be the sum of the biorientations for the individual segments.

In Fig. 18a, for example, infinity line 74 is shown as intersecting overlapping vectors 75a and 75b (spaced apart for illustrative purposes only). As shown, the derived orientation for the grouping is 0 since there are only two vectors in the group. As indicated previously, this value is derived from the sum of the two individual orientations, which are 1 and -1, respectively. The biorientation value for the example of Fig. 18a will be 2, which is the sum of the biorientation values for the individual segments. It can be seen that the biorientation value for the grouping is simply a count of the number of segments in the grouping.

Note that a grouping of two segments is considered to be a construct known as a "bigon," that is a polygon formed from two sides. Therefore, since two overlapping segments form substantially a polygon of two sides, the grouping in Fig. 18a is properly termed a bigon. Presently, the biorientation value for a bigon conveys another piece of information, which is whether the bigon represents a collapsed hollow or solid. At present, a bigon having a positive biorientation value is assumed to represent a collapsed solid. The bigon illustrated in Fig. 18b represents a collapsed hollow. In actuality, at this level of processing, both situations in Figs. 18a and 18b would be given the same physical orientation. Therefore, although useful for understanding the process, the orientation depicted in Fig. 18b would not really be created in the present embodiment. All bigons are treated as enclosing a trapped positive area. Therefore, they are considered to enclose their area in a counterclockwise manner. However, at later processing stages, including

the union operation to be described shortly, there two situations are treated differently due to the fact the other vectors on the layers inherently indicate that one of the bigons is within a solid region, and the other is within a hollow region. The vectors of Fig. 18a are drawn as a portion of the object whereas the vectors of Fig. 18b are not drawn since they merely represent a double exposure of a particular area.

In the differencing and intersection operations (after a complementing operation) to be described hereinafter, these bigons will be distinguished from one another by having opposite signs being assigned to their biorientation values. This is important, since it provides the ability to retain collapsed features that might otherwise be lost.

The previously depicted infinity lines were straight lines running parallel to the x-axis, with imaginary bends placed in the lines for utilization in determining orientations of segments which run parallel to the x-axis. However, it should be understood that the physically significant features of the lines are that they start at a point of known quantitative volume and that they are continuous. As such, the orientation of each of the vectors in the segment list can be determined by a single curved infinity line that intersects each of the vectors, wherein the infinity line starts at a position of known quantitative volume, and wherein the orientation of the vectors is determined by the upward or downward transition of the quantitative volume between 0 and 1. In addition, the orientation of each vector should be labeled such that the vectors are given a direction which points to the right of the direction (at the point of contact) of the infinity line when the transition is from hollow into solid and to the left when the transition is from solid into hollow.

The case of three overlapping segments 76a, 76b, and 76c is illustrated in Figs. 19a and 19b. The infinity

line intersecting the vectors is designated with numeral 77. Fig. 19a illustrates the case where the infinity line enters the grouping of three segments from a hollow, while Fig. 19b illustrates the case where the infinity line enters the grouping of three segments from a solid.

The segments which make up the grouping are shown spaced apart for illustrative purposes only, and the respective changes in the value of QV is shown. Note that in Fig. 19a, the value of the orientation is 1, all in accordance with the sum of the individual orientations, while the orientation value in Fig. 19b is -1.

In both cases, however, the grouping comprises both a collapsed hollow, and a collapsed solid. Therefore, the biorientation value for both cases is assumed to be 3.

This completes the discussion of the particular approach currently used to assign orientations to segments in the first embodiment. Turning back to Fig. 14, in step 58, the projection segments are sorted by minimum y, and then in step 59, merged with the segments in the segment list. Note that the segments in the projection list already have orientations assigned to them, and do not have to have orientations derived for them as per the segments in the segment list. The orientation for the vectors in the projection list is determined in a manner analogous to that used for determining orientation for the near-flat boundary vectors described in previously referenced and incorporated PCT Publication WO 89/10256. Merging the segments for the two lists together paves the way for taking the union of the areas encompassed by the segments of both sets, which union, as discussed previously, will result in the formation of the layer boundaries.

In step 60, the union operations are performed. To perform the union operation, a series of infinity lines will be run through the segments in the merged list. Then, the QV value will be computed at each intersection point (here, unlike step 57, the QV values are derived

from the segment orientations), and any segment where the QV makes a transition from below 1 to a value of 1 or greater, or a transition from above 1 or exactly 1 to less than 1 will be retained. All other segments will be discarded. The retained segments, as will be seen in the discussion below, will form the union of the areas encompassed by the segments in the segment and projection lists.

This operation is illustrated in Fig. 20a, which shows segments forming two loops, one loop assumed to be formed from segments in the segment list, the other assumed to be formed from segments in the projection list. In general, there is at least some overlap (matching vectors) between those in the segment list and those in the projection list.

A plurality of infinity lines 78a-78f are shown intersecting the segments, and after the intersection points have been determined and located, the QV values are determined. The QV values are shown in the figure. Using the retention rule discussed previously, the retained vectors are labelled as A-I. These segments are redrawn for clarity in Fig. 20b, with the excluded segments, J-M, shown as dashed lines. As shown, the area encompassed by the retained segments is the union of the two areas shown in Fig. 20a. It should be recalled that the decision to retain or remove vectors was based on whether the transition across the vector included quantitative volume changes between at least 0 and 1 inclusive.

For the retained segments, any orientation value greater than 1 is changed to 1, and any orientation value less than -1, is changed to -1. By this process, overlapping segments are effectively discarded. Moreover, the biorientation values for these segments is reset to 1. However, note that some segment groupings will still be retained. These include bigons representing collapsed solids. Bigons representing collapsed holes are dis-

carded. Then, the retained segments are reconnected to form polygons.

Discarding collapsed holes reflects the policy of this embodiment that solid features are considered more important for accurately representing the object than hollow features. To implement this policy, when a bigon is encountered, in the union operation, a new parameter, QV', is defined. To determine QV', the value of the biorientation parameter, rather than the orientation parameter, is added to the QV value just prior to the bigon, and the resulting value analyzed. If the transition from QV to QV' goes from below 1 to 1 or greater, the bigon is retained; otherwise, the bigon is excluded. The orientation parameter is never used since it will be 0, and will never cause a transition in the QV.

Turning to Figs. 21a and 21b, the treatment of bigons in this union operation will be described in greater detail. These figures show bigons being intersected with infinity line 79. The value of QV will be unchanged, as indicated, on either side of the bigon since the orientation parameter is 0, but the value of QV', which is the value of QV with the biorientation parameter added to it, makes a transition compared to the QV value just prior to entering the bigon to 2 (from 0) in Fig. 21a. As a result, the bigon is retained. The situation depicted in Fig. 21b is similar to that depicted in Fig. 18b. The biorientation of this figure is +2. Therefore, upon crossing the segment, the QV' goes from 1 to 3. Since it does not go through the range 0 to 1, this bigon would therefore be removed. As a result, in the union operation, it is seen that the bigons which form independent structure are kept while the bigons which duplicate structure are removed.

This completes the steps illustrated in Fig. 14.

Turning back to Fig. 13, in step 38, line width compensation (LWC) is next performed. First, it should be understood that the layer boundaries for each layer define

a polygon, and the first step of LWC is to move the vertex points of each polygon so that the cure width of the material, which forms upon exposure to a beam of the synergistic stimulation, will be entirely encompassed within the polygon. For each vertex, a path known as a vertex bisector will be formed to define a path for the vertex to migrate along. Each bisector will be situated to bisect the angle formed at each vertex. This step is illustrated in Fig. 22a, which shows polygon 80, with vertices 81a, 81b, 81c, and 81d. The corresponding vertex bisectors are illustrated by the dashed lines emanating from each vertex. The vertex bisectors form the path along which each vertex will be migrated until the cure width along the border will be entirely encompassed within the border. The cure width of the material which results from the exposure of the material to the beam of the synergistic stimulation is identified by numeral 84. In the following discussion, this will be referred to as the beam trace.

Focusing on vertex 81c for the moment, the vertex will be migrated along the bisector to point 81c', which is defined as that point at which the beam trace will entirely fit within the confines of the polygon 80.

The beam trace will typically be in the shape of a circle as shown. In this instance, the migration of the vertex point, which is identified by numeral 82 in the figure, will be continued until the shortest distance from the migrated vertex point to the sides of the polygon, which shortest distance is generally along lines which are perpendicular to the sides of the polygon, identified by numerals 83a and 83b in the figure, are equal to the radius of the beam trace. This situation will generally occur, as illustrated in the figure, only after the vertex point has been migrated by more than the radius along the bisector line.

Each vertex is then adjusted in order.

After adjusting the vertices as described above, the LWC algorithm will next perform a series of adjustments in case the vertex point may have migrated too far. An example of this situation is shown in Fig. 22b, where the above approach has given rise to unacceptable migration along the bisector line at a sharp vertex. The extent of this migration is unacceptable since it may cause unacceptable distortion in the final object. For example, the shaded area in Fig. 22b represents the distortion in the final object, since this area, although encompassed by the layer boundary 86, will not be exposed. As indicated, this distortion can be substantial.

Therefore, to reduce the distortion which may result in these extreme cases, the LWC algorithm limits the length of migration of any vertex point to a value which is the square root of two times the radius of the beam trace:

sqrt (2) x r

In Fig. 22c, for example, in which like elements are referenced with like reference numerals compared to Fig. 22b, the migration of the vertex point will be limited to 88a', and will not be allowed to proceed to 88a, as shown in Fig. 22b. When the beam trace is limited to 88a', the migration distance 85' is equal to the value specified above. The resultant beam trace will then be 87a' instead of 87a, as shown in Fig. 22b.

Note that this approach still results in some distortion, identified by the cross-hatched areas in Fig. 22c, and in fact even introduces some distortion. However, the intended result of limiting migration is to reduce the resultant distortion from what it was previously, and it has been found that limiting migration accomplishes this result in a wide variety of circumstances, even though distortion is not completely limited.

The LWC algorithm performs another adjustment to prevent undue migration. To perform this adjustment, the LWC algorithm first forms a displacement vector, defined

as the vector which points from the original to the migrated vertex point. The LWC algorithm will next double the length of the displacement vector along the bisector line, and if the doubled displacement vector crosses a segment on the polygon, the migrated vertex point is adjusted back towards the original vertex point until the doubled displacement vector just touches the intersected segment.

This process is illustrated in Figs. 22d and 22e, which shows polygon 80 with vertex point 81b, and segment 92. As shown in Fig. 22d, after the vertex point has been migrated to 90, the displacement vector 89 is doubled to obtain the doubled displacement vector 91 shown in phantom. As shown, the doubled displacement vector intersects segment 92, so as shown in Fig. 22e, the vertex point is migrated back to 90', towards its original location, so that the resulting displacement vector 89', when doubled to obtain vector 91' (shown in phantom), does not intersect, but, in fact, just touches vector 92.

A third adjustment performed by the LWC algorithm is triggered when two displacement vectors cross, as shown in Fig. 22f, which shows displacement vectors 94a and 94b, for vertices 81a and 81b, respectively, crossing at intersection point 93. In this instance, the migrated vertices are moved back to the intersection point 93 so that the resulting displacement vectors do not cross each other.

A fourth adjustment is triggered when the displacement vector crosses a compensated segment (a compensated segment is the segment that results from connecting migrated vertices). This situation is illustrated in Fig. 22g, which shows polygon 95, and compensated segment 97'. Segment 97' is obtained by migrating vertex points along displacement vectors 96a and 96b, and then connecting the migrated points. Also shown is displacement vector 96c. This displacement vector has resulted from the migration of a vertex point opposing segment 97', and has intersected the compensated segment 97'. In this

instance, the LWC algorithm will move the compensated segment (not the vertex point as per the adjustments above) back towards the original segment it was derived from, keeping it parallel with the original segment, until the cross over is eliminated. In Fig. 22g, the original segment is designated by 97, and the moved compensated segment, designated by identifying numeral 97", is shown in phantom. As shown, the moved compensated segment is parallel with the original segment 97. Alternatively, the compensated segment 97' can be moved back towards the position of the uncompensated segment while simultaneously shortening the displacement vector 96c so that the final segments meet near the middle of the uncompensated region thereby resulting in a better approximation to the most proper locations of the final compensated segment.

After all the vertices has been migrated, they are connected to form the compensated segments. This completes the line width compensation process.

Turning back to Fig. 13, in step 39, a series of boolean intersections are next performed to form the non-overlapping regions U[i]', D[i], and L[i]'''. The specific boolean operations which need to be performed are illustrated in Fig. 3, steps 17-21. Each of these steps comprises a boolean subtraction of one area from another or of one set of areas from another set of areas, which, as indicated previously, is equivalent to performing the boolean intersection between one area and the complement of the other. This section will explain the first embodiment of the implementation of the intersection operation. In the following discussion, it is assumed that the two polygons to be differenced are denoted as A and B.

The first step in this implementation is to take the complement of B. This is accomplished simply by breaking up the B polygon into its constituent segments, ordering the segments by their minimum z component, as described earlier, and then reversing, i.e., negating the orientation and biorientation values of each segment. For bigons

representing collapsed solids, this step has the effect of turning these into bigons representing collapsed hollows.

The second step in this implementation is taking the intersection between A and the complement of B. To accomplish this, in a similar manner to that already described for B, polygon A is divided up into its constituent segments, and reordered by minimum z. Then, the list of segments for both A and the complement of B are merged. Upon merging the sets, crossing points of intersecting vectors are determined and the intersecting vectors are split into smaller vectors at these points. A further step then takes place on the merged segments, whereby overlapping segments are used to form segment groupings, such as bigons, which were discussed previously. A special case occurs if a first segment overlaps a second longer segment. In this instance, the second segment will be split up into a third segment of equal length to the first segment, and a fourth segment which is the remainder. The first and third segments are then combined into a bigon.

After the above steps have been accomplished, the merged segments are intersected with a plurality of spaced infinity lines, and the orientations of the segments are then used to derive the QV values associated with various portions of the infinity lines. Only if a segment triggers a transition in the QV value from below 2 through or to the number 2 or vice-versa (through the range of 1 to 2) will the segment be retained. All other segments will be discarded. The result is the boolean difference between the two polygons or sets of polygons.

The above differencing step is illustrated in Fig. 23a-23c. Fig. 23a illustrates the two polygons to be intersected, numeral 100 designating polygon A, and numeral 101 designating the complement of polygon B. These polygons are shown as separated for ease of viewing. As illustrated, the segments which make up polygon A, illustrated by reference numerals 100a, 100b, 100c, and

100d, are oriented in a counter-clockwise direction, while the segments which make up the complement of polygon B, identified by reference numerals, 101a, 101b, 101c, and 101d, are oriented in a clockwise direction, which is reversed from polygon A because of the complementing operation.

Fig. 23b illustrates these same segments after overlapping segments have been split up to form bigons, after these segments have been ordered by their minimum z component, and then intersected with a plurality of infinity lines which are sufficient in number so that each segment is intersected at least once. For example, segment 100c is split up into segments 100c' and 100f, and then segments 100f and 101c are merged to form a bigon. In addition, segment 100d is split up into segments 100d' and 100e, and then segments 100e and 101d are merged to form a bigon. The QV values associated with different portions of the infinity lines are shown directly adjacent to the corresponding portion of the infinity line. Each infinity line is assumed to originate at infinity, but unlike the union operation discussed previously, where the infinity lines were given an initial QV value of 0 (consistent with the assumption that they originated in a hollow region), here, each infinity line is given a QV value of one. This is because here, it is assumed these segments originate in a solid region, consistent with taking the complement of B.

Considering infinity line 102a first, the QV values associated with this line makes a transition from 1 to 2 as the line passes segment 100b, and makes a transition from 2 back to 1 as segment 100a is crossed. Therefore, these two segments will be retained.

Considering infinity line 102b next, the QV values associated with this line makes a transition from 1 to 2 as it crosses segment 100b, makes a transition from 2 back to 1 as segment 101b is crossed, makes a transition from 1 back to 2 as segment 101a is crossed, and then makes a

transition from 2 back to 1 as segment 100d' is crossed. Therefore, segments 100b, 101b, 101a, and 100d' will be retained by virtue of this infinity line. Turning to infinity line 102c next, the QV value for this line makes a transition from 1 to 2 as segment 100b is crossed, changes from 2 back to 1 as segment 101b is crossed, and doesn't make a transition as segments 101d and 100e are crossed. (Note: These segments actually overlap each other and are shown offset from each other in the figure for illustrative purposes only. Therefore, since these segments overlap each other, and actually form a bigon as will be discussed subsequently, the QV value doesn't change.) Therefore, by virtue of this infinity line, segments 101d and 100e will be discarded.

It should be noted that the transition across the bigon will actually be more complicated than indicated above, and will take account of the biorientation value of the bigon, as discussed previously. Here, the biorientation value of the bigon will be 0. This is because the biorientation value for 101d will be 1, while for 100e, it will be -1. The sum of these two values determines the biorientation value of the bigon. Therefore, the value of QV' after exiting the bigon (equal to the QV value just prior to the bigon) added to the bigon biorientation value will be 1. Since the value does not transition through or to 2, the bigon will not be retained.

Considering infinity line 102d next, the QV value for this line makes a transition to 2 as it passes through segment 100c', transitions back to 1 through segment 101b, and does not change as it passes through segments 101d and 100e. Moreover, the QV' value for this bigon is still 1. Therefore, by virtue of this infinity line, segment 100c' will be retained while decisions regarding the other crossed segments were previously made and remain uncontradicted by the present results (e.g., 101b to remain and 101d and 100e will be removed).

Considering infinity line 102e next, the QV value for this line does not make a transition as it passes through segments 100f and 101c, and also through segments 100e and 101d. In addition, the biorientation values for both these bigons will be 0. Therefore, the QV' values for these bigons will be 1. Therefore, by virtue of this infinity line, segments 100f and 101c will be discarded.

The end result is shown in Fig. 23c. A comparison with Fig. 23a shows that this polygon does, in fact, represent the boolean difference between polygons A and B.

Note that after the intersection operation, if any bigons had been retained, they would be converted back to individual segments. The orientation value for each segment while part of the bigon would be retained, but a biorientation value of 1 would be assigned to each segment.

Turning back to Fig. 13, the next implementation step to be discussed is skin retraction step 40. Skin retraction is performed during the vector generation step 24 in Fig. 3b. Basically, in general terms, the net result of skin retraction is the retraction of skin vectors slightly at points where the vectors would otherwise intersect or overlay the borders used to generate these vectors. The benefits of performing skin retraction are to reduce over-exposure of certain areas, also to prevent the filling of areas too small to benefit from skin vectors and to prevent generation of excess skin vectors which must be stored and/or processed resulting in less efficient operation of the system, all of which were described previously.

Skin retraction is performed by adjusting all the borders (up-facing, or down-facing) inwards to create phantom borders while still retaining the original borders. The skin vectors and/or possibly hatch vectors are then generated from the phantom borders using the skin generation algorithm to be discussed subsequently. The original borders are retained, since these, not the

phantom borders, will be used to create the border vectors. Skin retraction, or more appropriately hatch retraction can be done in the layer borders L" or on the separate sets of layer borders L''' and up borders U' for the purpose of generating retracted hatch.

The phantom borders are generated from the original borders, in steps 16, 22, and 23 in Fig. 3a.

The adjustments made to the original borders in order to arrive at the phantom borders, is much less elaborate than line width compensation.

Basically, the only step performed is to displace, towards solid area, each border vector by the UBO or LBO value, while keeping each border vector parallel to the original border vector along with a substep of clipping vectors. Once the phantom borders are created, they will be converted into phantom segments. There is no need to split segments since crossing or overlapping segments will be processed properly by the algorithm.

Once the phantom segments have been created, the next steps are to merge them with the original border segments, and then sort the merged segments by the minimum-y dimension. Next, these segments are rotated, if necessary, in preparation of intersecting these segments with a plurality of spaced, parallel, horizontal infinity lines. Next, quantitative volume analysis is successively performed for each skin line to generate the skin vectors. As before, each infinity line is assumed to originate at infinity, and has a quantitative volume value of zero at infinity. Next, considering each infinity line in turn, the quantitative volume value for each infinity line is incremented by the orientation value of each segment it crosses. When a transition is made from below 2 to or through 2, the generation of a skin vector at the intersection point is begun, and when a transition is made from 2 or above 2 to below 2, the generation of a previously-commenced skin vector is stopped. Note that this operation is very similar to the intersection

operation described previously except boundaries are not actually fully determined.

Skin vector generation is illustrated in Figs. 24a-24c. Fig. 24a illustrates borders 103, and phantom borders 103', which may either be layer or up, down-facing borders, overlayed with infinity lines 104a, 104b, 104c, and 104d.

Presently, preferred algorithms for generating hatch and fill only do so by creating vectors parallel to the x-axis. Therefore, if hatch or skin vectors are to be generated parallel to a direction other than that of the x-axis, the boundary of the area being considered is rotated by an appropriate angle, the appropriate hatch or fill vectors are generated, then both the boundary and hatch or fill are rotated back. This effect is shown in Fig. 24b. The rotated original borders are designated with numeral 103", and the rotated phantom borders are designated with numeral 103'''.

Then, quantitative volume analysis is performed along each of the infinity lines. At each intersection between a line and a segment, the quantitative volume number for the segment is incremented by the orientation value for the segment. Taking infinity line 104b as an example, at intersection point 105, the quantitative volume number for the segment is incremented by the orientation value for segment 103a" (which is 1), to arrive at a quantitative volume of 1. Next, at intersection point 105', the QV value makes a transition to 2. Therefore, at point 105', the generation of hatch vector 107 is begun. Next, at point 106, the orientation number for segment 103b'" (which is -1) is added to quantitative volume number to arrive at a quantitative volume of 1. (QV values are indicated on the corresponding portion of the infinity line to which they apply). Since the quantitative volume value has made a transition from 2 or above 2 to below 2, the generation of skin vector 107 is ceased at point 106. Next, at point 106', the QV value makes a transition to 0,

which has no effect on the skin vector generation process. This completes the formation of skin vector 107. This analysis is successively performed for each of the infinity lines which intersect the segments.

Note that skin retraction only, and not hatch retraction, is performed in the this embodiment. However, hatch retraction could be performed as well in a similar manner to that described above for skin vector retraction, and is intended to be included within the scope of the subject invention.

Turning back to Fig. 13, in step 40, the rest of the vector types are generated, including border and hatch vectors. The border vectors are simply determined from the border segments, and the hatch vectors are determined from the border vectors in a manner similar to that described above for the generation of skin vectors, with the exception that the spacing of the hatch vectors will typically be wider than that for the skin vectors.

Skin retraction is accomplished by moving the vertices of up or down-facing borders (already adjusted for line-width compensation while still part of the L border) inwards, then connecting the moved vertices to create phantom borders, and then generating the skin vectors from the merged set of original and phantom borders.

It is accomplished by migrating the vertices along vertex bisectors (as with LWC) until phantom borders drawn from the migrated vertices have been moved inwards by an appropriate amount (about one-half the cure width) from the original borders. If phantom borders from opposing sides touch, or cross over each other, then skin vector generation will automatically be suppressed in those areas since transitions to 2 or above 2 will not be made. Two illustrative examples are provided in Figs. 25a-28c.

Fig. 25a illustrates a hollow four-sided pyramid 120 (only one side is visible in this sideview) framed by two slicing layers 121a and 121b to form cross-section 116.

The layer boundaries for this cross-section are designated by numerals 117a and 117b. Fig. 25b illustrates a top view of these layer borders.

The phantom borders for borders 117a and 117b are shown in phantom (by dashed lines), and identified with identifying numerals 117a' and 117b'. As shown, the phantom borders cross; therefore, no skin vectors are generated. As movement is made along an infinity line which crosses the combined real and phantom borders, the transitions in QV are from 0 to 1 to 0 to 1 to 0 on one side and then 0 to 1 to 0 to 1 to 0 on the opposite side. This is indicated by the series of 0's and 1's at the bottom of the figure. Since no transitions through the range 1 to 2 occur, no skin or hatch is generated.

Another example is shown in Fig. 25c, in which the phantom border for border 118 is identified with reference numeral 119. The phantom border 119 comprises phantom borders 119a and 119b. As shown, the phantom borders for the top portion 118a of border 118, have collapsed into phantom border 119a, and are therefore discarded, while the phantom border 119b for the bottom portion 118b of the border 118 have not collapsed, and are therefore retained. As a result, skin vectors will only be generated for the area encompassed by phantom border 119b.

Next, in the creation of phantom borders, several additional steps are performed to further increase resolution and to avoid possible problems. First, the phantom borders at corners, where the angle of the corner is less than 180° as traversed through hollow, are clipped or rounded to further increase resolution, and to avoid the problem of not producing sufficient skin to prohibit possible drainage in the supposedly solid portions of these corners.

An example of clipping is shown in Figs. 26a-26d. Fig. 26a depicts a cross-section of an object along with various real borders and phantom borders that would be produced without utilization of clipping methods. The

area 123 between outer boundary 121 and inner boundary 122 is an up-facing area of the layer and the area 124 enclosed by inner boundary 122 is a continuing area. Since area 123 is an up-facing area, skin fill vectors will be generated. However, the skin vectors will be formed in a reduced area 127 which is a subarea of area 123. This sub-area is located between outer phantom border 125 and inner phantom border 126 (drawn in phantom) due to skin retraction as discussed earlier. Phantom borders 125 and 126 are the borders which would be used to determine skin placement if clipping methods are not used. The amount of retraction used in creating phantom boundary 125 from real boundary 121, and phantom boundary 126 from real boundary 122, is typically somewhat less than the cure width associated with curing a vector to a depth equal to that which boundaries 122 and 121 will be cured with.

Fig. 26b depicts the same cross-section as Fig. 26a including the real cross-sectional boundaries 122 and 121. Surrounding boundary 122 is contour line 128. Contour line 128 represents the horizontal extent of cure that occurs when boundary 122 is traced with a beam of synergistic stimulation which induces a cure width of dimension 131. A contour which depicts the inner extent of cure when boundary 122 is cured is not shown since the entire area within 122 will be cured due to the size of the area and the width of cure associated with the beam. It can be seen that the extent of cure near vertices 132a, 132b, and 132c does not form sharp corners of cured material, but instead produces curved regions of cured material of radius similar to that of the cure width. The area cured when boundary 122 is exposed is represented by number 133 and is shaded by small dots. In a similar manner, when boundary 121 is exposed, the area 136 (represented by small dashes) between inner contour 134 and outer contour 135 is cured. From considering vertex 137, where two non-collinear boundary vectors meet, it can be seen that on

the side of the vectors at the vertex where the angle between the vectors is greater than 180°, the extent of cured material will form a smooth curved surface whereas on the side of the vectors at the vertex where the angle is less than 180°, a sharp corner will be formed.

Fig. 26c depicts the same cross-section as did Figs. 26a and 26b. Real boundaries 121 and 122 are depicted as well as phantom boundaries 125 and 126. Typically, when skin fill is exposed up to a boundary, the cured material associated with the skin fill will extend somewhat beyond the line of the boundary. When clipping methods are not used, skin fill is exposed between phantom boundaries 125 and 126. Contours 138 and 139 depict the extend of cure associated with curing the skin fill vectors up to phantom boundaries 125 and 126, respectively. Therefore, associated with the skin fill is cured material 140, extending between contours 139 and 138. This is depicted in this figure using small dots.

Fig. 26d again depicts the same cross-section, but this time, with the cured area described in association with Figs. 26b and 26c superimposed. This superposition indicates that there are several regions 141a, 141b, and 141c, within the region that should have been entirely cured, but that did not get cured. Consideration of this figure, as well as of the previous three Figures, indicates that when two non-collinear vectors meet, there is an inner and outer edge of cured material associated with the junction, the outer edge being on the side of the vectors where the angle is greater than 180°, while the inner edge is on the side of the vectors where the angle is less than 180°. When curing material along the vectors, the inner edge always forms a sharp point and the outer edge always forms a curved region of transition from one vector to the other. This curved transition region always extends too little along the bisector of the angle, and this lack of extension becomes more severe as the inner angle becomes smaller. Therefore, when one is

curing material in association with a portion of an original boundary that contains inner and outer sides, and wherein that portion of the original boundary is being offset in the direction of the outer edge of the boundary so that a secondary (phantom) boundary is formed which is to act as an inner side of a region to be cured, a difference in extent of cure occurs which results in an unexposed region of the part.

Since such uncured regions are undesired, ~~a~~ method of "clipping" has been developed which substantially eliminates the problems of uncured regions, at the cost of possible minor excess exposure in these regions. This method of clipping involves the creation of phantom boundaries that more closely resemble the cure that results from the exposure of the original boundaries. This correction to the phantom boundaries need only occur when the phantom boundary which is being created is offset from the original boundary toward the outer edge of a junction (of two vectors). This is how clipping is implemented in the presently preferred embodiment. Clipping is implemented when the junction is being offset in the direction of its outer edge, that is when the junction is being offset towards the side of the junction which has an angle which is greater than 180°.

It may be conceptually more convenient to literally offset all vectors, and for clipping to occur at all junctions followed by removing any negative areas which may be created. Alternatively, it may be more convenient to literally offset all vectors, recompute the intersection points, and form clipped vectors when an intersection point does not exist due to consecutive vectors no longer intersecting each other after the offset.

A method of implementing clipping, as applied to the example of Figs. 26a-26d, is depicted in Figs. 27a and 27b, along with a first alternative being described in Figs. 27c and 27d.

Fig. 27a depicts the same cross-section as did Figs. 26a-26d. Boundaries 121 and 122 are depicted along with vertices 105a-150g and associated vertex offset vectors 151a-151g. These offset vectors indicate the direction along which the vertices will be offset to form the phantom boundaries 125 and 126 of Fig. 26a. It can be seen that vertices 150a-150d are offset toward the inner edge of their respective junctions (toward the side which is formed by an angle less than 180°) while vertices 150e-150g are offset toward the outer edge of their respective junctions (toward the side which is formed by an angle greater than 180°). In this implementation, those vertices which are offset toward the inner edge are offset in a manner analogous to that described for cure width compensation. In other words, the vertex points are moved to the tips of their respective offset vectors. However, the vertices that are to be offset toward the outer edge are not shifted along a single displacement vector. Instead for this embodiment, each of the single angle bisecting displacement vectors 151e-151g are replaced by two displacement vectors, one associated with and perpendicular to each segment forming the junction. These two new offset vectors continue to indicate an offset to the same side of the junction as did the original offset vector. These new offset vectors are indicated in Fig. 27b, in which original offset vector 151e has been replaced by offset vectors 152a and 152b, original offset vector 151f has been replaced by offset vectors 152c and 152d, and original offset vector 151g has been replaced by offset vectors 152e and 152f. These offset vectors are formed by splitting the single vertex point into two vertex points along lines perpendicular to each junction vector individually. It can be seen in the figure that when both ends of a junction (boundary) vector are offset in this manner, this offsetting does not result in a change in length of the vector. Original boundary vectors 159, 160, and 161 become phantom vectors 155, 153, and

157, respectively. However, when a vertex is offset in this way, the original junction vectors are no longer adjacent. Instead, the splitting of the single vertex into two vertices results in the creation of an intermediate segment which connects the two vectors together. Such intermediate phantom segments are depicted in Fig. 27b as vectors 154, 156, and 158 for original vertices 150f, 150g, and 150e. These intermediate vectors are called clipping vectors since they clip off a portion of the area which would be incorporated on the inner side of the junctions if the vertices were allowed to offset in the previously described manner. It can be seen, by comparing Figs. 26a, 26b, 27a and 27b, that the phantom boundary comprising phantom vectors (or segments) 153-158 more closely approximates the outer extent 128 of the region cured when exposing boundary 122 than did the phantom boundary 126 obtained by the previously-described approach. This more accurate approximation forms the phantom boundary which will be used for determining the extent of cure associated with skin fill. Therefore, this more accurate approximation removes the undesirable untransformed regions 141a, 141b, and 141c of Fig. 26d that would typically be formed by the non-clipping approach described earlier.

Figs. 27c and 27d depict another way of conceptually understanding and implementing clipping methods of skin retraction. Instead of offsetting vertices, all vectors can themselves be shifted perpendicular to themselves by the desired amount. This is indicated in Fig. 27c where vectors 159, 160, 161, 162, 163, 164, and 165 are the original vectors which, when offset, produce phantom vectors 155, 153, 157, 166, 167, 168, and 169 which are offset by the proper amount in the proper directions. It can be seen that all vectors retain their original length. Each boundary and phantom vector in the figure also contains an arrow head which indicates its respective orientation. Next, each pair of successive vectors, that

no longer adjoin head to tail, have the gap bridged by the creation of an additional vector which is oriented in a manner compatible with the orientation of the pair. Several such bridging vectors are indicated in Fig. 27d. Vector 171 bridges vector 166 to 167, 172 bridges 167 to 168, 173 bridges 168 to 169, 170 bridges 169 to 166, 158 bridges 157 to 153, 154 bridges 153 to 155, and 156 bridges 155 to 157. Next, at points where vectors cross-over, they are split into smaller vectors, so that independent polygons can be formed. These polygons are then evaluated to see if they should be retained for use as phantom borders for skin fill production. If a polygon is determined to contain negative area, that is if the quantitative volume associated with it is determined to be negative, it is removed from further consideration as a possible phantom border. On the other hand, if a polygon is determined to contain a quantitative volume with a positive or zero net value, it is retained as a phantom border.

An additional alternative method is to use the approach just described for offsetting entire vectors, followed by the creation of properly oriented bridging vectors for those pairs of successive vectors that no longer touch or cross each other (as described above). This is followed by the determination of intersection points (new vector heads and tails) for those pairs of successive vectors that did crossover each other, which is followed by the splitting of vectors where they crossover each other (this pertains to non-successive vectors), which is followed by the determination of consistently oriented polygons (all vectors in the polygon have compatible orientations). These polygons remain for further processing and removal of inconsistently oriented polygons, (where one or more vectors within a polygon have incompatible orientations), followed by the removal of polygons which contain negative areas. The remaining

polygons are used to form the phantom boundaries which are used in determining extent of skin fill.

The computer software used to implement the first embodiment is advantageously written in the C language, and executes on an NEC, Silicon Graphics, or IBM compatible computer or the like. This computer is known as the SLICE computer, and is a component in an overall stereolithography apparatus described PCT Publication WO 89/10256.

The SLICE computer typically generates the border, hatch, and skin vectors. However, other embodiments are possible, including a "slice on the fly" implementation, whereby the SLICE computer generates the border vectors only, and distributes hatch and skin vector generation to the PROCESS computer. Moreover, the PROCESS or SLICE computers need not be single computers, but can be a multi-processor configuration, in which parallel processing is employed. Also possible is an optical computer embodiment. Although no optical computers are presently available commercially, current research indicates they show promise in performing boolean operations optically. The proceedings of the 10th International Optical Computing Conference of 1983, contains a paper by J. Tanida and Y. Ichioka entitled "Optical Logic Array Processor" which gives further details on this topic. This referenced paper is fully incorporated by reference herein as though set forth in full.

Typically, the SLICE computer specifies the desired layer thickness for each layer, either from user input or from the data obtained from the external source, slices the object representation accordingly, and then passes this data to the PROCESS computer, which in turn directs a recoating means to provide a layer of stereolithography material having the specified layer thickness.

Because of the finite tolerance of the layer recoating process, it may not be possible to obtain a

layer of material exactly of the desired layer thickness. Instead, it may only be possible to obtain a thickness which is within a few mils (i.e., 2-3 mils) of the desired thickness.

Therefore, as an alternative to the above, a "recoating on the fly" algorithm is possible (which is to be distinguished from the "slice on the fly" algorithm discussed previously), whereby recoating takes place first, the precise layer thickness is determined, and then the slicing algorithm is executed to slice the next layer representation out of the object representation, using this previously-determined layer thickness. The advantage of doing so is to ensure exact correspondence between the assumed layer thickness (which determines the exposure of the synergistic stimulation to be used to trace the layer) with the actual layer thickness. If the assumed value of thickness is greater than the actual value, then the present layer will be overcured by more than the desired amount into the previous layer, which can lead to associated distortion problems. If the assumed value of thickness is less than the actual value, then the present layer will be overcured by less than the desired amount into the next layer, which can lead to associated adherence problems. Exact correspondence between these two values will eliminate these two problems. Additionally, if a recoating method is used which is not self-compensating, as was the previously-described embodiment, then any slight error in thickness may continue to build up from layer to layer resulting in a final part whose vertical dimensions are out of tolerance.

A second and most preferred embodiment of the subject invention will now be described. This embodiment is very similar to the first embodiment. Therefore, only those aspects of the second embodiment which are deviations from the first embodiment will be emphasized.

As an overview of these deviations, a significant aspect of this embodiment is the ability to accept, as

input, border representations of a three-dimensional object as opposed to just a tesselated triangle formatted object representation as per the previous embodiment. As a result, this embodiment can accept input directly from a CAT Scan system or the like, which provides input in the form of a plurality of spaced, cross-sectional scans of a three-dimensional object. Each of these cross-sectional scans will include information descriptive of the borders of each scan, and this is the information which this embodiment requires. Of course, this embodiment retains compatibility with the tesselated triangle formatted object representation as per the first embodiment, which is provided by most commercial CAD systems. Another deviation of this embodiment is the orientation values assigned to the segments. In the previous embodiment, all segments were oriented according to the right hand rule, and segments pointing downwards were assigned an orientation value of 1, while those pointing upwards were assigned an orientation value of -1. In this embodiment, this is reversed, with upward-pointing segments being assigned an orientation value of 1, and downward-pointing segments being assigned an orientation value of -1. Then, to compute the QV value along the infinity lines, at the intersection points with the segments, in the course of performing a union operation, intersection operation, hatch generation, or skin generation, the orientation values are subtracted from the QV value just prior to intersecting the segment, instead of being added to this QV value as per the previous embodiment. Therefore, the target transition values for all these operations can remain the same.

Another important aspect of this embodiment is its ability to slice larger stl files with less or no use at all of virtual memory. In this embodiment, an stl file is read, the triangles are sorted by their minimum z values, and the sorted triangle data is output to a temporary file. Then, the SLICE program only brings into memory the

triangle data pertaining to a desired range of layers as opposed to holding the whole stl file in memory during the processing. After processing the various layers that a particular triangle pertains to, the triangle is discarded from memory. This reading in of only necessary triangles results in two significant benefits: (1) More memory is left available for the slicing process thereby reducing the need for memory swapping to the hard disk, and also resulting in faster slice times for files that would have required memory swapping; and (2) the need for maintaining large quantities of memory is reduced thereby reducing the cost of the computer system.

Various alternative schemes can be used that lead to various additional advantages. The first of these alternatives is to not create a sorted stl file but to instead create a table, by scanning the stl file, that contains information on how many triangles are associated with each layer. Then, each time additional triangle data is needed, the file can be scanned and triangles loaded into memory until the proper number of them have been loaded. This has somewhat of a disadvantage in processing time over the previous approach but has the advantage of not requiring hard disk space to store an extra (sorted) stl file.

A second alternative or set of alternatives is with regard to loading in as much of the stl file as possible but avoiding the need to utilize time-consuming virtual memory. The amount of memory needed to process a given layer is, to a large extent, based on the number of triangles that contribute to vector formation on that layer. Therefore, an embodiment can be used where the number of triangles associated with the necessary process for each layer can be determined. This information can then be matched to the estimated amount of additional memory needed to process the triangular data into vectors. Then, the optimum amount of input data can be read in at the optimum times in order to minimize the number of disk

accesses and to maximize memory use thereby minimizing the slicing time associated with large files. For some files, these techniques will not only optimize the slicing process, but they may be necessary to ensure the ability to slice extremely large files with a reasonably priced and sized computer.

This completes an overview of the major deviations. A flowchart of the second embodiment, provided in Figs. 28a-d will now be discussed.

Turning to Figs. 28a-28d, the elliptically shaped polygons represent starting and stopping points of SCHLEISS, the rectangular-shaped polygons all represent process steps, the diamond polygons all represent decision points, and the trapezoidal-shaped polygons all represent input or output files. As indicated previously, for each process step, the flowchart indicates the particular SCHLEISS module, and the line number within that module, where that particular process step is executed.

In step 200, the SCHLEISS program is started. In step 201, the memory manager is initialized. Briefly, the memory manager allocates and deallocates memory in response to requests by the various SCHLEISS functions. In step 202, the time counter is initialized. Briefly, this counter is incremented as the execution of the program progresses, and is used to keep track of and possibly record the execution times of the various SCHLEISS functions.

In step 203, SCHLEISS obtains the specifications for slicing from the user. As indicated, the user information is obtained from both command line 204 and from arg file 205. In step 206, SCHLEISS writes out the user-specified parameters to both msg file 207, and screen 217. The screen is the output screen for viewing by the user, while the msg file is simply a file where this information is stored.

In step 208, a query is made as to the type of input. As indicated previously, the input may either be in the

form of triangles, or alternatively, may be in the form of border representations known as polylines.

The situation where triangles are input will be considered first. In step 209, the triangles are obtained from stl file 216. In step 210, the triangles are rotated, scaled, or translated according to the user-specified parameters. Next, in step 211, the x, y, and z coordinates of all triangle vertices are rounded to slice units, and in addition, the z coordinates of all vertices are rounded to the nearest slicing plane. Only the z coordinates are so rounded since the z-axis is the assumed slicing axis. Then, in step 212, a query is made to determine which triangles are flat triangles. Then, in step 213, all flat triangles are deleted. Flat triangles are deleted, since they are redundant to the other triangles in terms of creating layer boundaries. In step 214, a query is made as to whether any triangles remain in the stl file. If so, a loop is made back to step 209, and steps 209-214 are repeated until no further triangles are available.

In step 215, the triangles are sorted by the minimum z coordinate of any of their vertices. In step 218, the sorted triangles are written out to tmp file 219. In step 220, the "current layer" indicator is initialized to the first layer to slice. In the current implementation, this is the first layer of the object which is comprised of data obtained from between the first and second slicing planes. The created cross-sectional data is then associated with the z value of the upper slicing plane. In step 221, the previous layer, i.e., region below the first slicing plane (which yields data) is sliced yielding the null set of vectors.

Slicing is done in the manner described previously with respect to the first embodiment, to obtain a net layer boundary comprising intersections between the triangles in the tmp file 219 and the two slicing planes bounding the layer. In step 223, this boundary is beam

compensated in the manner described previously with respect to the first embodiment.

Then, in steps 224 and 226, the current layer is sliced and compensated using the triangles in tmp file 219, to form a boundary for the current layer utilizing intersections between the triangles and the slicing planes bounding the layer. Next, in steps 227 and 229, the next layer is sliced and beam compensated to provide a beam-compensated boundary for the next layer in the manner previously described with respect to the first embodiment. These compensated boundaries are the singly adjusted layer boundaries, L[i]', discussed previously. Next, in step 230, any down-facing region associated with the current layer is computed by taking the boolean difference, between the layer boundaries for the current layer and the previous layer. These boundaries are used to generate the FDB vectors previously described with respect to the first embodiment.

In step 231, any up-facing region for the current layer is computed by taking the boolean difference between the current layer boundary and the next layer boundary.

In step 232, the hatch region for the current layer is computed as the boolean difference between the current layer boundary and the boundary for the down-facing regions.

In step 233, the layer boundaries are compensated by removing up-facing regions from the area encompassed by the hatch boundary. This is accomplished by taking the boolean difference between the hatch region and the up region. These layer boundaries are the thrice-adjusted layer boundaries, L[i]'", and are used to generate the LB vectors as previously described. In step 234, the LB vectors for the current layer are written out to sli file 235.

In step 236, any up-facing boundaries are adjusted to remove any down-facing regions encompassed by these boundaries. This step is performed in order to prevent

the down-facing regions from getting over-cured. These boundaries are the adjusted up-facing boundaries, U[i]', discussed previously, and are used to generate the FUB vectors. In step 237, the FUB vectors are written out to sli file 235. In step 239, the hatch region is hatched in the manner described previously. Hatching results in the LH vectors described previously. In step 240, the LH vectors for the hatch region are written out to the sli file.

In step 241, the down-facing regions are hatched. These regions are hatched separately from the rest of the layer boundary so they will not be overcured. This step results in the NFDH vectors described previously. In step 243, the FDB and NFDH vectors are written out to sli file 235. In step 245, the up-facing boundaries for the up-facing regions on the current layer are retracted in the manner described previously. In step 246, the fill vectors for the retracted up-facing boundaries are generated in the manner described previously. This results in FUF vectors. In step 247, the FUF vectors are written out to sli file 235. In step 249, the down-facing boundaries are retracted in the manner described previously. This step results in the adjusted down-facing boundaries, D[i]'. In step 250, the fill vectors (the FDF vectors) for the down-facing regions are generated in the manner described previously, and in step 251, these vectors are written out to sli file 235.

In step 253, a query is made to determine if the current layer is the last layer in the stl file. If not, in step 267, the "current layer" indicator is set to the next layer, and steps 227, 229-234, 236-237, 239-241, 243, 245-247, 249-251, and 253, previously described, are repeated for this layer. When all layers have been processed, in step 268, messages regarding missing or misoriented segments are written out to the output screen 217, and to msg file 207. In step 271, memory usage

messages are written out to the screen and msg files. In step 272, the process is considered completed.

Turning back to step 208, the case where the inputted data is already in the form of layer boundaries will now be described. As indicated, the input data should be in the form of polylines. These are obtained from slc file 256.

In step 254, the polylines for a given layer are obtained, and in step 255, these polylines are rotated, scaled, and translated according to user-specified parameters, in a similar manner to that described previously for the triangles.

In step 257, the polyline vertices are rounded to sli units, and the z-component of each vertex is rounded to the nearest slice layer.

In steps 258-259, all polylines having an inputted layer thickness of 0 are deleted, since these layers represent layers which have collapsed upon rounding, and which therefore, are redundant.

In step 260, any gaps in the polyline contours are filled by generating additional segments to fill in the gaps, and in step 261, a user-specified flag is checked to see if misdirected segments are to be reoriented. If so, in step 262, one attempt is made to reorient any misdirected segments in a polyline contour. This can be detected, since all segments within a polyline contour are expected to obey the right hand rule, whereby segments in a contour enclosing a solid do so in a counter-clockwise direction, while segments in a contour enclosing a hollow do so in a clockwise direction. For example, if all segments in a contour except one follow a counter-clockwise oriented loop, these segments are assumed to enclose a solid, and the direction of the one segment will be changed to be consistent with the others.

If the user-specified flag is not set, a jump is made to step 264. In this step, adjusted segments are combined as much as possible.

In step 263, the polylines are written out to tmp file 219.

In step 266, a query is made as to whether any additional layers exist in the sli file. If so, steps 254, 255, 257-264, and 266, described previously, are repeated for each layer in the sli file. Then, a jump is made to step 220, and the same process described previously, beginning with step 220, is performed using the tmp file 219.

The above completes a description of a flowchart of the implementation of the second embodiment.

Another file, SMAKE, when executed, calls SCHIRIS.MAK, which, in turn, appropriately combines S0.C to S6.C, and S.H.

In the previously-described embodiments, the resulting object will be oversized compared to the original representation of the object. In essence, the oversizing is not in the vertical dimension of the object formed, it is basically in the horizontal dimensions of the object formed. However, whenever a horizontal dimension is cured in excess, a corresponding cure of one layer thickness will result in the region where there should have been a cure thickness of something less than one layer thickness. As described previously, the accuracy of reproduction of an oversized object can be increased substantially by sanding off the discontinuities between layers in the regions of the object, whose design did not specify such discontinuities (corresponding to sloped regions in the original design). Objects formed by this oversized style basically have at least a portion, on each layer, of their surface that match the envelope of the object representation while the other portions of the surface of the formed object extend the solid portions of the object beyond the envelope.

There are other styles that lead to other sized objects, wherein these other sized objects have advantages in terms of object buildability, or in terms of object

accuracy. One such embodiment forms undersized objects that are in essence opposite to the oversized objects previously described. Such an undersized style is disclosed in previously referenced PCT Publication WO 89/10256. Objects formed by this undersized style basically have at least a portion, on each layer, of their surface that match the envelope of the object representation while the other portions of the surface of the formed object do not extend the solid portions of the object up to the envelope. A basic form of this style can be easily implemented by a slight modification to the earlier described embodiments of the present invention. The modification involves a change in the information and boolean operations used to form the initial layer boundaries for a given cross-section. These layer boundaries L[i] are derived by finding the intersection of the area of the S[i-1]+ borders with the area of the S[i]- borders. In this embodiment, the projection information is not used. After formation of all of the L[i] boundaries, the previously-described operations are used to determine layer boundaries for each layer. This undersized embodiment is particularly useful when discontinuities are to be filled in. This filling in can be done by application of a post-processing technique which fills the discontinuities with material and transforms this material to become part of the final object. Alternatively, and more preferably, this filling in of discontinuities can be performed on a layer-by-layer basis as the object is being formed. Techniques for, and advantages of methods for achieving such coatings are described in Section 3 of this detailed description entitled "Improved Surface Resolution By Inclusion Of Thin Fill Layers.

Another style produces objects which are more undersized than those of the previous embodiment. This style is used to build objects whose maximum solid extent does not result in the appropriately registered reproduced

object and object representation envelope contacting each other. This type of sized object is useful when, after formation, the entire surface of the object is to be coated, even in areas that do not contain discontinuities, with a material (e.g., paint, powder coating, metallic coating). So that the surface of the coated object will more closely match the envelope of the object representation, the entire surface of the object must be retracted into the solid regions. This building style can be implemented by the techniques of the present invention. It requires layer comparisons (especially differencing) to offset the down-facing and up-facing features away from their original positions by the appropriate amount (this amount should be approximated by an integral number of layer thicknesses) so that the down-facing and up-facing portions of the object do not contact the object envelope. It also requires a form of LWC or boundary retraction so that horizontal solid portions of the layers can be retracted away from the object envelope.

A style calling for an averaged sized object can also be implemented based on the techniques of the present invention. This implementation involves the use of additional slicing planes which are located, one each, midway between the slicing planes used to define the positions of triangle vertices of the object representation. The initial layer boundaries L[i] are determined from intersections of the intermediate (midpoint) slicing planes with the triangles that form the representation of the object. These initial layer boundaries are processed according to the teachings previously disclosed to determine up-facing, down-facing, and net layer regions for each cross-section of the object. These initial layers boundaries are conceptually associated with the higher of the two original slicing planes which bound the vertical extent of the layer. After determination of the various net regions associated with each cross-section (or layer), an object can be formed which will be of

average size as compared to the objects built by the undersized and oversized styles previously described. In other words, the discontinuities which form due to the object being reproduced on a layer-by-layer basis, wherein the layers have finite thickness, are formed half extending beyond the envelope of the object and the other half falling short of the envelope.

Fig. 29a depicts a two dimensional view, the two dimensions being the vertical dimension and one horizontal dimension, of an object envelope 540 of an object which is to be formed by stereolithography. Planes 500, 502, 504, 506, 608, 510, 512, 514, and 516 depict the vertical position of the slicing planes which bound the vertical extent of each layer to be formed and define the possible vertical locations that triangle vertices can be rounded to, whereas slicing planes 520, 522, 524, 526, 528, 530, 532, and 534 define the vertical dimension from which intersection segments with the triangles will be obtained. The data obtained from slicing plane 520 will be associated with slicing plane 502, since it represents the average positions of the cross-sectional information between slicing planes 500 and 502. Similar up-shifting of data obtained from the other intermediate slicing planes will occur. Fig. 29b depicts the same object envelope 540 superimposed over layers of the object formed using an oversized building style. Fig. 29c depicts the same object envelope 540 superimposed over layers of the object formed using an undersized building style. Fig. 29d depicts the same object envelope 540 superimposed over layers of the object formed using an average sized building style. Examination of these figures indicate why each style was so named. The oversized style is useful when post-processing involves material removal techniques; the undersized style is useful when post-processing or layer-by-layer processing involves filling techniques; and the average size style is useful when it is desired to

have reasonably high accuracy without any additional processing.

Cure Width Compensation

As previously-described, if any cure width compensation is desired it can be implemented prior to the determination of the three independent regions of a layer. Alternatively, it may be implemented after the three independent regions are determined, thereby allowing different compensation values for each region. However, when following this alternative approach it is necessary to compensate the boundaries properly. When following this alternative approach, all the LB[i] vectors are compensated inward (normal compensation). The DB[i] and UB[i] vectors that were derived, as per the subject invention, from the boundaries of the previous or next layer by comparing the uncompensated layer boundary for a present layer to the uncompensated boundaries of the previous and next layers, respectively, should be compensated outward (reverse compensation). The DB[i] and UB[i] vectors that comprise boundaries of the present layer (before separation into three regions) are compensated inward, and the UB[i] vectors that are derived from the DB[i] vectors of the present layer (prior to compensation) are compensated inward. The amount of compensation of these vectors may differ according to the sources from which they are derived. LB[i] vectors are compensated by an amount A[i]. UB[i] and DB[i] vectors, which are derived from the uncompensated boundary of the next or previous layer, are compensated by the amount A[i]. UB[i] and DB[i] vectors, which are derived from the uncompensated boundaries of the present layer, are compensated by an amount B[i] and C[i] respectively. UB[i] vectors which are derived from the DB[i] vectors of the present layer are compensated by an amount C[i]. This compensation can be done by shifting the vectors and recalculating end points or by shifting the end points initially. The value

A[i] represents one-half the width of cure associated with curing of the LB[i] vectors, B[i] represents one-half the width of cure associated with the curing of the UB[i] vectors, and C[i] represents one-half the width of cure associated with the DB[i] vectors. Since many methods utilizing the techniques of layer comparison (especially those of the concurrently-filed applications) might lead to extreme variations in cure depth (and associated cure width) this alternative approach is most preferred so that individual regions can be more accurately compensated.

These principles can be illustrated with reference to Figs. 30a-30f, in which like elements are referenced with like reference numerals.

Figs. 30a-30c illustrate the uncompensated layer boundaries, identified with reference numerals 600, 602, and 604, for layers i-1, i, and i+1, respectively, and the compensated layer boundaries, identified with reference numerals 601, 603, and 605, respectively, for these layers.

Fig. 30d illustrates compensating the vectors that make up the down-facing boundary for layer i. The uncompensated down-facing boundary is identified with numeral 606, and the desired compensated down-facing boundary is illustrated with numeral 607. As indicated, the vectors in the uncompensated down-facing boundary that do not touch the uncompensated layer boundary from the previous layer, identified with numerals 606a and 606b, are compensated inward to obtain compensated vectors 607a and 607b. By contrast, the vectors in the uncompensated down-facing boundary that do touch the uncompensated layer boundary from the previous layer, identified with numerals 606c and 606d in the figure, are compensated outward to obtain compensated vectors 607c and 607d.

Turning to Fig. 30e, the compensation of the net up-facing vectors is illustrated. The uncompensated net up-facing boundary for layer i is identified with numeral 608, while the desired compensated boundary is illustrated

with numeral 609. As indicated, the uncompensated net up-facing vectors which do not touch the uncompensated layer boundary from the previous layer, identified with numerals 608a and 608b in the figure, are compensated inward to obtain compensated vectors 609a and 609b, respectively. By contrast, the uncompensated net up-facing vectors which do touch the uncompensated layer boundary from the previous layer, identified with numerals 608c and 608d in the figure, are compensated outward to obtain compensated vectors 609c and 609d, respectively.

Turning to Fig. 30f, the uncompensated net layer boundary for layer i, identified with numeral 610, is compensated inward to obtain compensated net layer boundary 611.

While embodiments and applications of this invention have been shown and described, it should be apparent to those skilled in the art that many more modifications are possible without departing from the inventive concepts herein. The invention, therefore, is not to be restricted, except in the spirit of the appended claims.

<u>Section 2</u>: <u>Simultaneous Multiple Layer Curing in Stereolithography</u>

A. <u>The simple case</u>

Data corresponding to an object to be built is sliced with a layer thickness less than or corresponding to the desired vertical resolution. Preferably, but not necessarily, the MSD is an integral multiple of this layer thickness.

In the normal practice of stereolithography the next step would be to build the object based on the created slices with each layer or slice being cured to a depth corresponding to the layer thickness. However, the next step in the implementation of the present invention is based on the fact that we cannot cure thicknesses of material as thin as the slices (at least unsupported thicknesses). Groups of these slices are compared to

determine on which layers various portions of each cross-section will be built. For this comparison the slices are grouped consecutively with each group containing a sufficient number of slices to form a thickness equivalent to the MSD. If the MSD is 40 mils and the layer thickness is 10 mils, each group will contain 4 cross-sections. In the first preferred embodiment of the invention, group 1 contains cross-sections 1, 2, 3, and 4, group 2 contains cross-sections 2, 3, 4, and 5, and group "N" contains cross-sections N, N+1, N+2, N+3.

Turning to the drawings, Fig. 31 shows a side view of an hourglass shaped object that can be built using stereolithography. For simplicity, Fig. 31 shows only one horizontal dimension "X" along with the vertical dimension "Z". The other horizontal dimension extends into the page 1 inch. In total, this drawing represents a rectangular hourglass.

Fig. 32 is a side view of the hourglass or object of Fig. 31 but this view shows the object as reproduced by stereolithography using 10 mil thick layers or cross-sections and a material whose MSD is less than or equal to 10 mils. The layers are designated by one of 4 symbols "." , "x", "+", or "o". The use of these symbols is only to emphasize the distinction between layers. The numbers to the right side of Fig. 32 designates the various layers. There are 28 layers derived from 28 cross-sections of data which are derived from 29 slicing planes. This method of obtaining cross-sectional data is described in WO 89/10256.

Fig. 33 is similar to Fig. 32 except that instead of 10 mil separation between cross-sections (i.e., 10 mil layer thickness) there is a 40 mil separation. when using a material with an MSD of 40 mils, in the prior art one would have to use 40 mil cross-sections or greater. Therefore this figure represents the best resolution possible with such a material using prior art techniques.

Fig. 34 represents an example of an alternative typical stereolithographic technique intended for achieving high resolution accuracy from a lower resolution material. Fig. 34 shows the object of Fig. 34 again depicted but built with 10 mil cross-sections along with a material having a 40 mil MSD. In the hope of obtaining better resolution using a 40 mil MSD material, one might try to slice the object using finer cross-sections but still solidifying it to a 40 mil cure depth. The result of doing this is shown in the Fig. 34 which illustrates that the steps between layers have been made smaller but that the vertical location of features is grossly inaccurate.

Fig. 35 represents the object of Fig. 32 again but now built using the techniques of the present invention along with 10 mil layers or cross-sections and a material of 40 mil MSD. Comparing Fig. 35 to Fig. 32, we see that we have produced an object while using a low resolution stereolithographic material which has the same degree of accuracy as when a high resolution material was used.

This result of obtaining the same degree of accuracy is not possible in the prior art. It should be noted that all objects cannot be built with this same degree of accuracy while using low resolution (LR) materials. The key to being able to obtain the same or better resolution than what is obtainable with high resolution (HR) materials using typical stereolithography is that the object cannot have vertical features that are thinner than the MSD of the lower resolution material. These features are "too thin". If an object has such vertical features then there will be a corresponding loss of reproduction accuracy. However, this loss of reproduction accuracy occurs only in the regions of these "too thin" features. Additionally, careful planning can reduce the adverse affect that these deviations have on the part. Techniques for handling such cases are described hereinafter. Included in these techniques are careful selection of the

slice axis; building along more than one axis as disclosed in U.S. Patent No. 4,575,330; and post processing by sanding or filling as may be generally required using standard stereolithography anyway.

To illustrate the conceptual details of accomplishing the reproduction depicted in Fig. 35, it is useful to compare the material cured in association with each layer in producing the objects shown in Figs. 32 and 35. Figs. 37 and 38 show these cross-sections and corresponding areas of cure for each of the 28 possible layers. Specifically, Fig. 37 shows the curing regions for each layer of the object of Fig. 32, and Fig. 38 shows the curing regions for each layer of the object of Fig. 35. In the following we refer to curing layer thickness depths of material. In actuality, we may cure somewhat more than this thickness where appropriate to get good adhesion between layers to enable formation of a cohesive three-dimensional object. As with standard stereolithography up-facing and down-facing features when cured must be skinned to prevent leakage if the objects are being built with crosshatch (as described in WO 89/10256 U.S. Patent Application S/N 331,644).

Keeping in mind the less than or equal to 10 mil MSD for Fig. 32, and the 40 mil MSD of Fig. 35, from Fig. 37 we see for cross-section 1 that a 10 mil layer of material is cured which forms the first layer of the object shown in Fig. 32. However from Fig. 38 we see that no material is cured in association with the first cross-section of the object of Fig. 35 since the minimum cure would have caused the formation of a layer that would have been 30 mils overcured. The second and third cross-sections shown in Figs. 37 and 38 depict similar situations.

The fourth cross-section begins to reveal a key aspect of the instant invention. In Fig. 37 the fourth cross-section shows the same cure as does the previous 3 layers. The fourth cross-section of Fig. 38 depicts the curing of material to form the first layer of the object

depicted in Fig. 35. The material cured in association with this cross-section penetrates down through the previous 3 layers to form a 40 mil thickness of material. This is identical to what we have formed up to this point for the object of Fig. 32. In essence the first 4 cross-sections of Fig. 38 were compared and a decision was made as to the inappropriateness of curing a 40 mil thickness of material in association with the first 3 cross-sections. A corresponding decision was made regarding the appropriateness of curing material in association with the fourth cross-section. We note that any time a region is first cured (therefore not supported by previously cured material) it must be skinned if the object is built with open spaced crosshatch, or else the down-facing features will leak and drain. Additionally, we note that when building a part utilizing the present invention we need only recoat in association with those layers with which curing will be associated.

The fifth cross-section of Fig. 37 cures down an additional 10 mils completing the No. 5 layer of the object of Fig. 32. The fifth cross-section of Fig. 38 is also cured but the ques-tion arises as to the depth of cure. The amount of untransformed material between the last cured cross-section (layer) and the material surface is 10 mils. This entire 10 mil gap (according to this embodiment) is to be filled in by solidifying the intervening material in association with the fifth cross-section. The MSD for the building material is 40 mils and represents the minimum unsupported solidifiable depth. However, when a region is completely supported, the "supported minimum solidification depth" (SMSD) is generally less than the MSD for a particular material. This minimum could conceivably drop from 40 to 10 mils or less. Therefore, the cure depth for this fifth cross-section can be anything greater than the greater of the SMSD or the 10 mil cross-section thickness (plus an overcure amount). The maximum cure depth associated with

this fifth cross-section is a depth that does not cause the bottom surface of the junction between solidified material and unsolidified material to grow down and thereby cause a significant change in accuracy of the lower surface or down-facing feature of the object.

Generally there is an associated change in beam cure width with a change in cure depth. One approach to handling this change in beam cure width is to allow a different beam width compensation factor for boundary types that are cured to different depths, as discussed in Section 1.

For the sixth through thirteenth cross-sections, each successive cross-section is smaller than and sits completely on or over the previous cross-section. The up-facing regions of each of these cross-sections can be cured in a different way from the non-up-facing regions if desired (e.g., up-facing regions skinned while non-up-facing regions only hatched). The explanation applied to the fifth cross-section above therefore also applies to these cross-sections.

The fourteenth through sixteenth cross-sections similarly completely overlap the preceding cross-sections so that no further explanation of these sections is necessary.

Cross-section 17 partially overlaps 16 but there are some regions which form down-facing features. Fig. 37 shows that the entire cross-section is properly cured to a 10 mil depth. The down-facing regions of the cross-section of Fig. 37 may be given different cure parameters than the non-down-facing regions, e.g., down-facing regions skinned and cured to a depth of 10 mils, non-down-facing regions only crosshatched and cured to a depth of 10 mils plus an overcure amount for adhesion.

Fig. 38 shows that only a portion of the layer is cured with the remaining portions uncured due to the inability to cure depths thinner than 40 mils. Hatched

areas of Fig. 38 represent cured portions. Phantom lines designate uncured portions of the layer.

Cross-section 18 has ends which are unsupported by the previous cross-section. Fig. 37 shows the whole cross-section being cured to a depth of 10 mils. Referring to Fig. 38, cross-section 18 has a first region that is supported by what was previously cured in association with cross-section 17, a second region that overlaps the portion of 17 that was not cured, as well as a third set of regions that do not overlap any part of cross-section 17. As Fig. 38 shows, only the supported regions are cured in association with this layer or cross-section.

The regions that overlap the portion of 17 that was not previously cured are now 20 mils thick. If we cure these regions at this time, in association with this layer, we would overcure them by 20 mils. Therefore, we do not cure these regions in association with this layer. The regions that do not overlap any portion of 17 should only have a 10 mil cure depth associated with them. We therefore also do not cure them with this cross-section.

Cross-section 19 again has ends which are unsupported by the previous cross-section. Fig. 37 shows the whole cross-section being cured to a depth of 10 mils. Referring to Fig. 38, cross-section 19 has regions that are supported by material that was cured in association with cross-section 18, another set of regions that overlap the portion of 18 that was not cured (actually these regions consist of two parts: one that overlaps uncured areas on both 17 and 18, and the other which only overlaps regions that were not cured in association with cross-section 18), as well as a third set of regions that do not overlap 18 at all.

As Fig. 38 shows, only the supported regions are cured in association with cross-section 19. The region that overlaps the portion of 18 that was not previously cured is now 20 or 30 mils thick depending on whether they

also overlap uncured material associated with cross-section 17. If we cure these regions at this time we would overcure them by 10 or 20 mils. Therefore, we do not cure these regions in association with this cross-section. If we cured the regions that do not overlap 18 at all then these regions would be overcured by 30 mils. Therefore, again, we do not cure these regions in association with this cross-section.

Cross-section 20 has ends which are unsupported by the previous cross-section. Again as expected, Fig. 37 shows the whole cross-section being cured to a depth of 10 mils. However, Fig. 38 shows something different about the curing of cross-section 20 as opposed to the curing of the previous 2 cross- sections. Cross-section 20 can be divided into 5 distinct sections:

1) the portion of the cross-section that does not overlap the previous cross-section (required thickness of cure 10 mils),

2) the portion of the cross-section that only overlaps the previous cross-section (required thickness of cure 20 mils),

3) the portion of the cross-section that overlaps the previous 2 cross-sections (required thickness of cure 30 mils),

4) the portion of the cross-section that overlaps the previous 3 cross-sections (required thickness of cure = 40 mils), and

5) the portion of the cross-section that overlaps material cured on the previous layer, i. e., the portion that overlaps the previous 4 or more cross-sections.

From this dissection of the cross-section, it can be seen that we can cure the fourth set of regions to a depth of 40 mils. This will cause the lower surface of solidified material to properly extend downward to the bottom of cross-section 17. As on previous cross-sections, we can also cure the fifth region any appropriate amount since it is supported. It should be

noted that in the actual curing process we would generally cure region 5 before region 4 and that region 4 must be skinned if the object is being built with open faced crosshatch. This is generally done when using a liquid medium to advantageously cure regions that are supported by previously cured material, before curing regions that are not supported by previously cured material. This is an advantageous method of curing because it allows each cured region to adhere to previously cured material whether through horizontal or vertical adhesion.

Cross-sections 21 through 24 are very much like cross-section 20 in that each of these cross-sections contain regions requiring 10, 20, 30, and 40 mil cures, along with deeper overlapping regions requiring any appropriate cure depth. Only the regions requiring the 40 mil cure and the supported regions are cured in association with each one of these layers. As expected, each of the cross-sections associated with Fig. 37 are cured in turn to a thickness of 10 mils plus any necessary overcure. Again, with regard to Fig. 38, regions requiring a 40 mil cure also require skinning if building with crosshatch.

Cross-sections 25 through 27 are again similar to cross-sections 21 through 24 in that they possess regions that can be cured to the proper depth (40 mils), regions that are supported, and regions that cannot be cured (without unacceptable introduction of error) due to the MSD. Again, the cross-sections of Fig. 37 are cured to a 10 mil depth. As usual for Fig. 38, regions of 40 mil depth must be skinned if building with crosshatch. Supported regions can be cured in any appropriate manner. The regions requiring less than a 40 mil cure are not cured in association with this cross-section but instead are cured in association with higher layers or cross-sections when the necessary MSD cure depth can be utilized without the introduction of errors.

Finally, cross-section 28 fully overlaps cross-sections 27, 26, and 25 and is therefore given an appropriate cure to form a cohesive cross-section of solidified material.

The foregoing comparison thus far has demonstrated the typical approach to stereolithography versus a particular embodiment for curing material using the present invention. This comparison, i.e., comparing Figs. 32 and 35, shows that the present method, even using a low resolution material, can generally closely match the high reproduction accuracy previously obtainable only by using a high resolution material.

Figs. 36 and 39 illustrate other embodiments. Comparing Figs. 35 and 36 illustrates that different cure patterns are used to cure material in association with each cross-section. Fig. 39 depicts the various cross-sections of the object of Fig. 36 and what will be cured in association with each layer. Fig. 39 can be compared to Fig. 38 (which illustrates the cross-sections of the object of Fig. 35) to reveal the differences between these two embodiments.

The Complex Case

Embodiments of the present invention embody a combination of two criteria. The first of these is based on the method of curing that will be used to emphasize maximum strength or other "internal curing order" related approaches. By "internal curing order" we refer to a variety of options utilized in the curing of an object that do not affect the external dimensions of the object. Two examples of this first criteria are depicted in Figs. 35 and 36.

The second criteria is based on the approach that will be followed to obtain a desired final object shape when the object has features smaller (i.e., thinner in the vertical dimension) than the MSD. Examples of this second criteria are shown in Fig. 43a through 43e. This second

criteria involves the selection of one of a variety of alternatives for obtaining the most appropriate reproduction of external features when it is impossible to create them as accurately as desired because of the MSD of the material.

The simple case, studied above, had a particular characteristic that made it possible to use a low resolution material along with a high resolution layer thickness to obtain reproductions that are equivalent to those obtainable from the use of a high resolution material and layer thickness. This characteristic is that the object has no vertical solid feature thinner than the MSD. This allowed slicing and curing of features such that inaccuracies in building would not be greater than the chosen layer thickness. It should be noted that most regions of most objects fit into this category. Therefore, a viable embodiment based on objects having no vertical features thinner than the MSD can be developed.

When a particular object to be reproduced has solid vertical features thinner than the MSD, the object can be reoriented for building by redefining the vertical axis of the object, thereby hopefully removing the thinner than MSD features. If the object cannot be reoriented there will be a loss of accuracy in creating these thin features.

This loss of accuracy can be manifested in two ways:

1) Thin features (i.e., features thinner than the MSD designated herein as "<MSD" features) will be made too thick; or

2) Thin features will not be cured and therefore will be completely removed. For clarity and brevity in the following description, thin features are always assumed to be cured. However, in other embodiments user options can be made available so that volume selections can be made so individual <MSD features can be cured to the MSD or not cured at all. This will not solve accuracy related problems as a whole but can certainly be used to de-

emphasize them by bringing out the more important features, namely solid volumes or hollow volumes. Additionally, if only a few regions of a part or object are over cured or under cured due to MSD limitations, minor post processing can generally be done to sand off or fill regions as needed.

Fig. 40 depicts a side view of another object that can be reproduced using stereolithography. This object has features a, b, c, and d which form thin vertical features. In building the object using typical conventional stereolithographic techniques, on a layer by layer basis, these features will naturally be removed or be formed to a thickness greater than or equal to the minimum vertical resolution (layer thickness) that the part is being reproduced with.

Fig. 41 depicts the prior art method of reproduction of the object of Fig. 40 using a high resolution layer thickness (e.g., 10 mils) and a high resolution material (MSD 10 mils).

Fig. 42 depicts the same object as reproduced using the present invention in combination with a high resolution layer thickness and a low resolution material (MSD = 4 times the layer thickness, e.g., 40 mils). This figure depicts an embodiment where the second criteria discussed above was chosen such that all object features thinner than the MSD were not formed.

Figs. 43a and 43b depict examples of several other embodiments where the other selections of criteria 2 are made. Fig. 43a depicts the reproduction of the object where priority is given to up-facing features. In other words, if a region is thinner than the MSD (i.e. too thin), material in the region will be cured in such away as to place the up-facing features in the positions where they would occur if a higher resolution material were being used. Correspondingly, the down-facing features will necessarily be cured to a depth below the level on which they would be formed when building with a higher

resolution material. This embodiment is referred to as "up-facing priority".

Fig. 43b depicts an embodiment where flat features are given priority thereby increasing aesthetic appeal of the object in some circumstances. The down-facing flat features and up-facing flat features are cured so that they are formed at the same position they would be formed at if a higher resolution material were being used. If regions exist that are both up- and down-facing so that both up- and down-facing flat features cannot be simultaneously cured to the desired level, the placement of down-facing flat features will dominate. The non-flat, sloped, features are pushed up or down. Therefore, they are formed above or below the level they would be formed at if the object were built using a higher resolution material. If two non-flat features oppose each other in a region that is thinner than the MSD, the features can be shifted proportionally according to the slopes of their upper and lower surfaces. Alternatively, the upper or lower surface may be placed at the position it would be formed at if a higher resolution material were being used. Fig. 43b accordingly illustrates a "flat priority/ down-facing dominate" embodiment.

Fig. 43c depicts an embodiment where features thinner than 1/2 of the MSD are not formed along with priority being given to up-facing features.

Fig. 43d depicts an embodiment where features thinner than 1/2 of the MSD are not formed along with priority being given to flat features.

Of course, the "1/2" parameter in the embodiments of Figs. 43c and 43d can be varied to any other fraction or percentage of the MSD.

Fig. 43e depicts an embodiment where down-facing features are given priority. The down-facing features are cured so that they are formed at the same position they would be formed at if a higher resolution material were being used. In contrast to the embodiment of Fig. 43a,

the up-facing features of Fig. 43e are pushed up above the positions they would actually be formed at if a higher resolution material were being used.

An Up-Facing Priority Embodiment

The following description sets forth a first preferred embodiment for obtaining the necessary information associated with each layer. This embodiment is based on the terminology and processing techniques of the Slice program as described in WO 89/10256.

This first preferred embodiment is based on the criteria that curing of features will occur in such away as to give priority to up-facing features (i. e., the second criteria discussed above). Therefore this embodiment is similar to the approach described in terms of Fig. 43a (up-facing priority). This criteria requires that boundary (and fill) information will be output on each cross-section as it is needed for proper placement and cure of up-facing features. If a region of a cross-section does not contain up-facing features, the region may or may not be solidified in association with the current layer. The layer on which the curing of a non-up-facing feature will occur depends on the MSD, the depth that solid extends below the region, and on strength and buildability criteria discussed above (first criteria). Up-facing features will be cured at their proper locations even if this causes the down-facing features to be cured too deep. The object will come out with the proper dimensions except where vertical features become thinner than the MSD and in that case the down-facing features will be inaccurate due to the extra cure.

In implementing the building method of the present embodiment (shown in Fig. 43a) we need to cure certain areas on each layer:

1) All areas of FUB (i.e., flat up-facing boundary), including placing of down-facing skin in appropriate regions;

2) All areas of NFUB (i.e., near-flat up-facing boundary), including placing of down-facing skin in appropriate regions;

3) All areas that are N layers thick including the placement of down-facing skin on these layers, where N equals the minimum solidification depth divided by the layer thickness (N = MSD/ZS). For example if the MSD is 40 mils and ZS is 10 mils then N equals 4; and

4) All areas that are greater then N layers in thickness.

Several methods for practicing this invention are possible. We could use operations such as comparing the areas on a pixel by pixel basis creating a net region of pixels indicating the interior of solid regions of a cross-section and those indicating net hollow regions and then creating boundaries at the border of regions where pixels are in one state versus the other. Another approach is to use the techniques described in Section 1. In Section 1 a method for determining net boundaries is based on the comparison of boundaries from different layers. The technique described in Section 1 may be applied directly to the present invention.

An object of the invention is to reproduce a part as accurately as possible using a Style 1 reproduction method. Style 1 is the designation, described in the previously referenced WO 89/10256 publication and in Section 1, given to the reproduction of an object that is based on discontinuities between cross-sections resulting in the oversizing of the X and Y dimensions of the object. This method allows the reproduction of a large class of objects which can be post processed, after formation, by sanding off the appropriate discontinuities to the point that they disappear. At the point of discontinuity

disappearance, the part is complete and represents a highly accurate reproduction of the object.

We consider the object to be conceptually sliced into a plurality of layers with each layer representing a structural portion of the object. In terms of the Slice program described in WO 89/10256, the structural portion of each layer comprises the area enclosed within the boundaries of the LB and NFDB. These combined boundary types are called the "Initial Cross-Section Boundaries" (ISCBS). The other boundaries define regions that need to be filled or skinned because they form up-facing or down-facing surfaces of the object but they do not form structure. That is, each initial slice cross-section (area contained within the Initial Cross-Section Boundaries) contains the necessary boundary information to form a layer of structure (if cured to one layer thickness) that will result in proper oversized X and Y dimensions. This oversizing is such that if appropriate removal of material along the edges of the part is done between the intersections of the present layer with the proceeding and succeeding layers, the layer of structure produced will match the original computer representation of the object accurately. This includes appropriate removal of discontinuities between layers as well as appropriate removal of material that was solidified so that hollow volumes were filled in.

Another desirable method of building, Slice Style 3, relates to the building of an object that is undersized in the X and Y dimensions. In the case of Style 3 the discontinuities between layers as well as regions that collapsed to zero thickness are filled in during post processing.

Additional styles of building are disclosed in WO 89/10256 as well as in Section 1.

We now describe generally the major steps involved in the first preferred embodiment (an up-facing embodiment). This description assumes that the MSD of the chosen

material is N times as large as the chosen layer thickness.

The preferred materials and sources of synergistic stimulation for utilization with the present invention depend on the layer thickness that will be used, the level of MSD that can be tolerated, and the accuracy of reproduction desired. A preferred material is XB 5081, manufactured by Ciba Geigy of Basel, Switzerland, which has an MSD of approximately 5 to 8 mils when used with a HeCd laser emitting 325 nm radiation. Therefore, using the prior art teachings of stereolithography, this material can be used to make high resolution parts of accuracy of 5 to 8 mils in vertical thickness (when only considering the sources of error addressed in the instant invention). This same material, in combination with the teachings of the instant invention and assuming an MSD of 8 mils, can be used to build many parts with an accuracy, for example, of 4 mils if N = 2, or an accuracy of 2 mils if N 4, or even an accuracy of 1 mil if N 8. Another preferred material is Potting Compound 363, manufactured by Loctite Corporation, which has an MSD of approximately 30 mils when used with synergistic stimulation from a high pressure mercury lamp, or alternatively Tevista Type I material, manufactured by Tokyo Ohka Kogyo Co. Ltd., Kanagawa Prefecture, Japan, which has an MSD of approximately 45-60 mils when used with synergistic stimulation from a high pressure mercury lamp. For example, when using a material like Tevista it may be advantageous to assume an MSD of 80 mils or more to ensure adequate strength under a wider range of building conditions. This assumed 80 mil MSD can still be used in a large number of objects according to the invention to yield a production accuracy of 40 mils when N = 2, or even 20 mils when N = 4.

Other preferred materials include powders and appropriate forms of synergistic stimulation as well as other fluid-like media. These powder materials when combined

with a particular type of synergistic stimulation may or may not have an MSD, as previously described. Even if this type of MSD doesn't exist for these materials they may have another type of MSD (as do photopolymers). This second type of MSD refers to a minimum solidification depth that results in formation of thicknesses of material that are sufficiently rigid or strong to withstand stresses that result from adhering layers together that would tend to "curl" distort the individual layers of the object and therefore result in distortion of the object itself. The ability of a layer of cured material to resist curl increases with increasing cure depth (for many materials it is proportional to the cube of the cure depth). Curl phenomena and several means of addressing this type of distortion are described in several of the previously referenced publications. Publications of particular interest are WO 89/10259, WO 89/10254, WO 89/10801, JP (x-y) and WO 91/06378.

Therefore, the formation process utilizing such materials can benefit from the deeper cure depths and thinner layers that can be utilized according to the present invention while maintaining little or no loss in placement accuracy. As such, the present invention is not only an extremely valuable method for achieving high resolution placement of features when using low resolution materials, but it is also an extremely valuable method of reducing curl distortion in objects when the desired accuracy of reproduction requires thinner layers than can normally be accommodated due to excessive curl distortion.

In an up-facing priority embodiment, up-facing features are given priority in terms of their placement and every attempt is made to cure down-facing features to the appropriate levels. In considering the steps involved in determining what should be cured in association with a cross-section I, we assume that the previous I-1 cross-sections have been formed in an appropriate manner.

First of all, the possible cure versus cure depth regions that might be encountered and that may need to be distinguished for making decisions about what areas should be cured on a given cross-section must be determined. In this description a building method similar to that depicted in Fig. 35, as opposed to that depicted in Fig. 36 is assumed. Therefore, whenever the depth of solidification is greater than the MSD there is always solidified material one layer thickness below the present level. We exclude Fig. 36 type building techniques, and the like, from further consideration in this analysis since their development will be within the ability of one of ordinary skill in the art after understanding the principles of the present disclosure. Table 1 shows a summary of the various cure depth regions.

Table 1

Summary Table of the various regions that can occur on a given layer when using an Up-Facing Priority Embodiment of Simultaneous Multiple Layer Curing.

Region Designation	No. of Previous Cross-Sections (Layers)	Thickness	No. of Higher Cross-Sections (Layers)
1	>= N	> = N+1	> = 1
2	N - 1	N	> = 1
3	N - 2	N - 1	> = 1
"	"	"	"
"	"	"	"
N - 1	2	3	> = 1
N	1	2	> = 1
N + 1	0	1	> = 1
1'	N	N + 1	0
2'	N - 1	N	0
3'	N - 2	N - 1	0
"	"	"	"
"	"	"	"

N - 1'	2	3	0
N'	1	2	0
N + 1	0	1	0

Region 1: This region is included on at least the next cross-section and on the present cross-section and on at least all N previous cross-sections. This region has a solidification depth, below the upper surface of the 1th layer, of at least N + 1 layers (MSD + 1 layer). Since we assume a Fig. 35 type building method, we know there is solidified material located in this region one layer thickness below the present level. We cure the material in this region with an appropriate cure depth that does not cause print through of solidified material below the solidification level of this region. We also know that the material cured in this region is not used to form a down-facing surface of the object or an up-facing surface of the object. Therefore, an open cure structure (open crosshatch) can be applied to this region if desired. Additionally, the formation of solidified material in this region is used to achieve adhesion between the layers. If N = 4, then this region is included on at least the previous 4 cross-sections.

Region 2: This region is included on at least the next cross-section and on the present cross-section and on all N-1 previous cross-sections. This region has a solidification depth, below the upper surface of the Ith layer of N layers. Since we assume a Fig. 35 type building method, this region has received no cure in association with previous cross-sections and therefore it is not cured for the purpose of adhesion to previous layers. Therefore, no overcure is necessary and it can be given a cure depth equal to the MSD. This causes the lower surface of the solidified material to be formed at the appropriate position to accurately reproduce the particular feature of the object that is being created. Since this region forms a down-facing surface of the

object it is cured in such away as to form a smooth lower surface. If N 4, this region is included on the previous 3 cross-sections.

Region 3: This region is included on at least the next cross-section and on the present cross-section and on all N-2 previous cross-sections. For accurate reproduction of the object, if this region were to be cured in association with the present cross-section, this region requires a depth of cure equal to the MSD less one layer thickness (MSD - 1 layer thickness). Due to the MSD, if this region is cured in association with the present cross-section, it will be cured 1 layer thickness too deep. However, since this region has at least one more layer of structure above it, we do not need to cure it in association with the present cross-section. We can postpone the curing of this region until at least the next cross-section is formed. This delay in formation will allow more accurate reproduction of the object. If this region is cured in association with the next cross-section it will be treated as a down-facing feature and maybe an up-facing feature if this region does not continue on beyond the next cross-section. If N = 4, this region is included on the previous 2 cross-sections.

Region N-1: This region continues on to at least the next cross-section and it is included on the present cross-section and on the 2 previous cross-sections (as long as N > = 2). This region cannot be cured in association with the present cross-section without causing an N-3 layer thickness error in the placement of the down-facing feature associated with the bottom of this region. As N becomes larger (assuming a fixed layer thickness and therefore and increasing MSD) so does the error associated with curing this region in association with the present cross-section. Since we know that there is at least one cross-section above this region, we know that we can delay the curing of this region until at least then. This postponing will allow more accurate placement

of down-facing features and therefore more accurate reproduction of the object. If N = 2, this region is region 1 and it therefore has similar characteristics to region 1 described above. If N = 3, this region corresponds to region 2, and it therefore has similar characteristics to region 2 described above. If N = 4, this region is Region 3 and it therefore has similar characteristics to region 3 described above. If N > = 4, this region is included on the two previous cross-sections (layers).

Region N: This region is included on at least the next cross-section and on the present cross-section and on the previous cross-section. If N = 2, this region is region 2 and therefore is similar to region 2 described above. If N = 3, this region is region 3 and therefore is similar to region 3 described above. If N = 4, this region is Region 4 and it includes the previous cross-section. With all cases where N 2, more accuracy in reproduction can be obtained by delaying the curing of this region until at least the next layer. This delay is possible since we know that this region continues until at least the next cross-section.

Region N + 1: This region is included on at least the next cross-section and on the present cross-section. It does not include any previous cross-sections. With all cases where N > = 2, more accuracy in reproduction can be obtained the curing of this region is delayed until at least the next cross-section. If N = 4, this is Region 5. If this region were cured in association with the present cross-section (assuming N = 4) then the bottom surface of this region would be placed 3 layers thicknesses below its desired location.

We next consider the regions labeled with a prime " , ". These primed regions are similar to the unprimed regions except they contain no additional cross-sections above them. Therefore, the primed regions form up-facing areas. With a building technique that calls for the

proper placement of up-facing features, these regions must all be cured on the cross-sections on which they occur.

Region 1': This region is included on the present cross-section and on at least all N previous cross-sections. This region is not included on the next cross-section. This region has a solidification depth below, the upper surface of the Ith layer of at least N + 1 layers (MSD + 1 layer). Since we assume a Fig. 35 type building method, we know there is solidified material located in this region one layer thickness below the present level. We therefore cure the material in this region with an appropriate cure depth that does not cause print through of solidified material below the solidification level of this region. We note that the MSD is the minimum solidification depth for an unsupported region and since this is a supported region it may be possible to use a cure depth smaller than the MSD. We also know that the material cured in this region is not used to form a down-facing surface of the object but it is used to form an up-facing surface of the object. Therefore, this region must be cured to form a uniform up-facing surface. Additionally, the formation of solidified material in this region is used to achieve adhesion between the layers. If N = 4, then this region is included on at least the previous four layers.

Region 2': This region is included on the present cross-section and on all N - 1 previous cross-sections. This region is not included on the next cross-section. This region has a solidification depth, below its upper surface of N layers. Since we assume a Fig. 35 type building method, this region has received no cure in association with previous cross-sections and therefore it is not cured for the purpose of adhesion to previous layers. Therefore, no overcure is necessary and it can be given a cure depth equal to the MSD. This causes the lower surface of the solidified material to be formed at the appropriate position to accurately reproduce the

particular feature of the object that is being created. This region forms both a down-facing surface and an up-facing surface and is therefore cured in such away as to form smooth lower and upper surfaces. If N = 4, this region is included on the previous 3 cross-sections.

Region 3': This region is included on the present cross-section and on all N-2 previous cross-sections. This region is not included on the next cross-section. For accurate reproduction of the object, if this region is to be cured in association with the present cross-section, it requires a depth of cure equal to one layer thickness less than the MSD (MSD - 1 layer thickness). Unfortunately, this cure depth will not form a cohesive layer of structure. Additionally, this region must be cured in association with the present cross-section. Therefore, there will be an error in positioning of the down-facing feature, below this region, of one layer thickness. This region has three attributes: 1) It is an up-facing region, 2) It is a down-facing region, and 3) when it is cured, it will be solidified 1 layer thickness too deep. If N = 4, this region is included on the previous 2 cross-sections.

Region N-1': This region is included on the present cross-section and on the 2 previous cross-sections (as long as N > = 2). This region is not included on the next cross-section. This region must be cured in association with the present cross-section but this will result in an error in cure depth of N - 3 layers. This region forms both an up-facing and down-facing feature of the object and it must therefore be cured appropriately. If N = 2, this region is region 1' and it therefore has similar characteristics to region 1' described above. If N = 3, this region corresponds to region 2', and it therefore has similar characteristics to region 2' described above. If N = 4, this region is Region 3' and it therefore has similar characteristics to region 3' described above.

Region N': This region is included on the present cross-section and on the previous cross-section. This

region is not included on the next cross-section. Since curing of this region must occur in association with the present cross-section, there will be an error in placement of the down-facing feature, below this cross-section, of N - 2 layers. This region is used to form both an up-facing and a down-facing feature of the object and therefore must be cured appropriately. If N = 2, this region is region 2' and therefore is similar to region 2' described above. If N = 3, this region is region 3' and therefore is similar to region 3' described above. If N = 4, this region is Region 4' and results in an error in placing the down-facing feature of 2 layer thicknesses.

Region N + 1': This region is included the present cross-section only. It does not include any previous cross-sections or any higher cross-sections. With all cases, where N = 1, this region must be cured in association with the present layer. It forms both an up-facing and a down-facing feature of the object and it will be cured N - 1 layers too deep. If N = 4, this is Region 5. In the case of N = 4, when this region is cured in association with the present cross-section, the bottom surface of this region will be placed 3 layers thicknesses below its desired location.

Having described the various possible regions that can occur on a given cross-section, we proceed with the steps required to determine the net cross-sections that will be used to form each layer in the process of building an object from a plurality of initial cross-sections.

We consider the "initial cross-sections" of an object to be those obtained using standard stereolithography. Each initial cross-section can be subdivided into several regions. These regions, as described above, are distinguished by the relationships between the present cross-section and the N proceeding cross-sections along with their relationships to the next successive cross-section. In association with a given cross-section all of the primed, " ' ", regions are cured along with

regions 1 and 2. Region 1 and 1' are used to assure adhesion between the present cross-section and the previous cross-sections. These regions have solidified material 1 layer thickness below them. Region 1' also functions as an up-facing surface and must be cured accordingly. Region 2 forms a downfacing surface and must be cured accordingly. Region 2' to region N + 1' form both up-facing and down-facing regions and must be cured accordingly. Region 3' to region N + 1' are the regions that are prematurely cured, due to the geometry of the object, and are therefore the regions that represent varying degrees of error introduced into the down-facing features of the reproduction.

After determining the extent of the initial cross-section boundaries for cross-section "I" we divide it into the various regions disclosed above. We proceed to divide the next initial cross-section "I + 1" into its appropriate regions. The primed regions of cross-section "I" do not contribute to any regions of cross-section "I + 1". All of the unprimed regions contribute to the next cross-section. The "1" region from cross-section "I" remains a "1" region for cross-section "I + 1" if cross-section "I + 2" still contains the region. If "I + 2" does not contain the region, the region becomes a 1' region. If "I + 2" partially contains the region, it becomes partially a "1" region and partially a 1' region. The other unprimed regions of cross-section "I" carry over to cross-section "I + 1" as primed or unprimed regions, or partially as both, depending on whether they continue on to cross-section "I + 2" or not. However, these other regions drop one region number with each succeeding layer until they get included into regions 1 or I' if they are not lost by inclusion in one of the higher prime regions prior to this.

For example, cross-section I, region 3 becomes cross-section "I + 1" region 2 or 2', etc. Therefore we can see how the different curing regions on each

cross-section are determined on successive layers based on the previous layers and on the initial cross-section boundary of the following layer. For example, cross-section 1 (the first cross-section of the object) can include only type N + 1 and type N + 1' regions. whereas cross-section 2 can contain type N + 1, N + 1', N, and N' regions depending on how the regions of cross-section 1 and cross-section 3 relate to cross-section 2, etc.

Section 1 discloses a layer comparison method to determine how to transform the object representation into buildable cross-sections. The primary embodiment of this section of the application is directed towards building oversized parts, but the techniques of the invention can easily be modified to produced undersized parts. Section 1 discloses methods of comparing successive cross-sections to determine the up-facing and down-facing features of each cross-section as well as the non-up-facing and down-facing regions.

The distinguishable regions described above associated with each initial cross-section were described in terms of relationships between the present cross-section and adjoining cross-sections. Therefore, a method of generically comparing neighboring cross-sections to determine overlapping regions (intersecting areas on two cross-sections) as well as non-overlapping regions (either included on one cross-section or the other cross-section but not on both) can be used to implement the present invention. There are various ways to optimize the processing of such information to obtain the regions, and their cure depths, associated with each layer. For example we may obtain the boundary (or area) data associated with each region on a given cross-section according to the steps described in Table 2. Table 2 depicts Boolean operations that can be utilized to obtain the regions described in association with Table 1 for an arbitrary cross-section I. These regions, as indicated,

are obtainable by intersection and differencing operations. These operations are performed on intermediate boundaries indicated by an * and initial cross-section boundaries of layer (I-1-N) up to layer (I+1).

Table 2

Summary Table of some possible area comparisons that can be used to obtain regional information for a given cross-section when using an Up-Facing Feature Priority Embodiment.

Step No.	Steps	Region
1	{I}(ISCB) n {I+1}(ISCB) = {I}(*)	
2	{I}(ISCB) - {I+1}(ISCB) = {I}(*')	
3	{I}(*) - {I-1}(ISCB) =	{I}(N+1)
4	{I}(*') - {I-1}(ISCB) =	{I}(N+1')
5	{I}(*) n {I-1}(ISCB) = {I}(N+1*)	
6	{I}(*') n {I-1}(ISCB) = {I}(N+1'*)	
7	{I}(N+1*) - {I-2}(ISCB) =	{I}(N)
8	{I}(N+1'*) - {I-2}(ISCB) =	{I}(N')
9	{I}(N+1*) n {I-2}(ISCB) = {I}(N*)	
10	{I}(N+1'*) n {I-2}(ISCB) = {I}(N'*)	
11	{I}(N*) - {I-3}(ISCB) =	{I}(N-1)
12	{I}(N'*) - {I-3}(ISCB) =	{I}(N-1')
13	{I}(N*) n {I-3}(ISCB) = {I}(N-2*)	
14	{I}(N'*) n {I-3}(ISCB) = {I}(N-2'*)	
15	"	"
16	"	"
17	{I}(5*) n {I+2-N}(ISCB) = {I}(4*)	
18	{I}(5*') n {I+2-N}(ISCB) = {I}(4*')	
19	{I}(4*) - {I+1-N}(ISCB)	{I}(3)
20	{I}(4*') - {I+1-N}(ISCB)	{I}(3')
21	{I}(4*) n {I+1-N}(ISCB) = {I}(3.)	
22	{I}(4*') n {I+1-N}(ISCB) = {I}(3'*)	
23	{I}(3*) - {I-N}(ISCB) =	{I}(2)
24	{I}(3'*) - {I-N}(ISCB) =	{I}(2')
25	{I}(3*) n {I-N}(ISCB) = {I}(2*)	

26 {I}(3'*) n {I-N}(ISCB) = {I}(2'*)
27 {I}(2*) - {I-1-N}(ISCB) = {I}(1)
28 {I}(2'*) - {I-1-N}(ISCB) = {I}(1')
29 {I}(2*) n {I-1-N}(ISCB) = {I}(N-2.)
30 {I}(2'*) n {I-1-N}(ISCB) = {I}(N-2'*)

where { } indicates the Cross-section Number
e.g., {I} = The Present Cross-Section indicates the
( ) indicates the particular region of the cross-section in the preceding (I.
e.g., (ISCB) = The Initial Cross-Section Boundary Area e.g., (N) = The Boundary Area of the Nth region
"n" = the intersection operation
"-" = the difference operation
"=" = the result of the particular operation

This generalized up-facing embodiment can be modified for utilization with materials that are not limited, for a given layer thickness, by the first type of MSD (inability to form a cohesive structure thinner than the MSD), but instead are limited by the second type of MSD (inability to form non-curling or low- curling layers thinner than the MSD when higher layers are adhered to them). In this case the primed regions of the previous disclosure can all be cured to the proper depth. This is because one doesn't need to worry about the next higher layer inducing curl in the material transformed in association with the primed regions of the present cross-section since the next higher layer doesn't exist above these regions. Therefore, each of these primed regions can be given the appropriate cure depth. The unprimed regions, on the other hand, must be cured according to the previous teachings. We can conclude that material/layer thickness combinations not limited by the first type of MSD but instead that are limited by the second type of MSD can be used to form all types of high resolution objects (of vertical resolution equal to the layer thickness) without loss of accuracy due to the misplacement of features and with only little or no loss of accuracy due to curl. This represents a significant improvement to the simple approaches to stereo-

lithography that don't address the issue of curl distortion. If this method doesn't completely lead to the desired level of curl reduction it can be combined with the other methods of curl reduction described in the previously referenced applications.

For combinations that are limited by both types of MSD an intermediate method can be developed that maximizes the overall accuracy of the object to be formed.

As with the above Up-facing Priority approach other approaches can be developed regarding the placement of features when regions become thinner than the MSD. Similarly other approaches can be developed regarding the curing of regions that are thicker than the MSD.

Down-Facing Priority

As with up-facing priority embodiments, as well as other priority embodiments, there are many methods for implementing a down-facing priority embodiment. These various methods may have their origin in different algorithms that are used to obtain the desired data or they may have their differences arise from the desire to obtain different types of data. For example, one embodiment may require knowledge of which regions are up-facing while another embodiment may not require such information. As another example, embodiments may differ due to the desired method of curing internal regions of the object. Such differences are depicted in the cure styles of Figs. 5 and 6.

A simple down-facing priority embodiment has one major aspect that differs form a simple up-facing priority embodiment. when a down-facing feature is encountered on a given layer "I", the area of the feature is conceptually pushed up through the next N-1 layers (assuming the MSD = N layer thicknesses). This down-facing feature will be associated with layer "I+N-1" for curing instead of layer "I" from which it was derived. This down-facing feature is cured to a depth equal to the MSD, thereby placing the

lower surface of the down-facing feature at the proper vertical level of the part. As a down-facing region is pushed up through the next N-1 layers its area is removed from curing consideration on the first N-2 of these higher layers.

This above discussion refers to layers not slicing planes. One can consider a down-facing feature to be found at a slicing plane which indicates the lower extent of a layer, whereas the vertical level or value associated with the layer is equal to the value of the next higher slicing plane. This next higher slicing plane indicates the upper extent of the layer which contains the down-facing feature. Presently preferred methods (as taught in the above referenced application) form down-facing features by curing them from the top of their associated layers down to the bottom of their layers.

The following steps can be followed in implementing a simple Down-Facing Priority Embodiment of the present invention. These steps are based on the ability to perform boolean layer comparisons as disclosed in Section 1. These steps can be performed by processing data one layer at a time followed by transformation of material for that layer (this does require some memory of previously formed layers and it does assume that knowledge about up-facing regions isn't necessary) and then processing the data for the next successive layer. This first possibility relates to slicing and obtaining data as needed. This is sometimes referred to as "Slicing on the Fly". Alternatively, these steps may be performed on a multiple layer basis prior to material transformation or on all the layers of the object prior to transforming material.

The procedure begins by processing each layer of the object according to the teachings of Section 1. One first obtains down-facing, up-facing, and continuing (volume) regions for each layer. Only the boundaries need be

determined for these individual regions. It is not necessary to determine crosshatch and fill at this point.

In standard stereolithography the $LB_1(I)t$ i.e., layer boundary vectors, are cured to a depth of 1 layer thickness plus any necessary overcure to obtain adhesion to the previous cross-section. The area within the $LB_i(I)$ can be cured in any appropriate manner including complete solidification (e.g., skintinuous methods as described in WO 91/06378 and further described herein after or partial solidification (e.g., hatching methods). Additionally, these areas can be cured by methods that include various curl reduction techniques (e.g., multipass, rivets, tiles, or the like).

Likewise in standard stereolithography, the $UB_i(I)$ are similarly cured except that the entire upper surface of the region must be transformed to form a smooth up-facing feature. The $DB_i(I)$ are to be cured to a depth of 1 layer thickness and are formed so that a substantially uniform cure depth is supplied so that a smooth down-facing feature is formed.

In the present embodiment, the $DB_i(I)$ are shifted up by N-1 layers to become the final down-facing boundaries of layer "I+N-1", $DB_f(I+N-1)$. This leaves the $UB_i(I)$ and $LB_i(I)$ associated with layer I.

Next, the $DB_i(I-N+1)$ are shifted up to layer I to become the final down-facing boundaries of layer "I", $DB_f(I)$.

Next, any area within the $UB_i(I)$ and $LB_i(I)$ which is also in the $DB_f(I)$ is removed from the UBi(I) and LBi(I) to form the first modified up-facing boundaries and continuing boundaries of layer "I", $UB_{m1}(I)$ and $LB_{m1}(I)$.

Next, the $UB_{m1}(I)$ and $LB_{m1}(I)$ undergo a second modification by removal of any intersecting area with the $DB_i(I-N+2)$ for N>2) yielding the $UB_{m2}(I)$and $LB_{m2}(I)$.

Similar modifications continue to occur until any down-facing features originally associated with the previous layer are removed from the $UB_{mn-2}(I)$and the LB_{mn-}

2(I)to form the $UB_{mn-1}(I) = UB_f(I)$ and the $LB_{mn-1}(I) = LB_f(I)$ wherein m = modification and n = N and f = final.

The $LB_f(I)$, $UB_f(I)$, and the $DB_f(I)$ represent the regions which will be cured in association with layer I. Appropriate cross-hatch, fill or other area transformation parameters are determined for these areas. Methods for making such determinations are described in detail in the previously referenced patent application.

The $DB_f(I)$ is cured to the MSD with appropriate parameters for creating a smooth lower surface. The down-facing features created by following these teachings will be appropriately placed.

The $LB_f(I)$ is cured to an appropriate depth which is generally greater than or equal to one layer thickness (the exact depth depends on the MSD for supported regions). By definition, there is material transformed one layer thickness below this region. Furthermore, by definition this region does not form an up-facing feature of the object. Therefore, this region can be cured to an appropriate depth to form an adequately cohesive layer as well as to ensure adequate adhesion to the previously cured layer of material without regard to the necessity of complete area transformation. Various curl reduction methods can be utilized in transforming this region, including an open crosshatch structure, if desired.

The $UB_f(I)$ region is cured to a similar depth as the $LB_f(I)$ region but the region is cured so as to form a continuously transformed upper surface resulting in a smooth up-facing feature.

This procedure is followed for all layers. The data obtained from this embodiment can be used to form a substantially high resolution object, wherein any deviations, due to features being thinner than the MSD, will result in placing the upper surfaces of the up-facing features out of position. Down-facing features will be accurately placed. This is indicated in Fig. 43e.

Other down-facing priority embodiments are possible as well as embodiments implementing the other styles of Fig. 43 or the like.

Even though the embodiments of this disclosure have been directed toward obtaining cure parameters through data processing, this only represents one approach to causing appropriate transformation of material in association with each layer. Therefore, the data processing terminology should be interpreted to include any means for modifying original object descriptive parameters that result in the transformation of material according to the teaching of this invention. The teachings of this invention relate to interpreting object descriptive parameters and reproducing the object in a manner which deviates from a strict layer by layer formation, as necessary to achieve a higher accuracy reproduction. The methods and apparatus of this invention lead to higher accuracy reproductions by utilization of the simultaneous multiple layer curing techniques disclosed herein.

Section 3: Curl Balancing

Referring now more specifically to Fig. 45 of the drawings, the stereolithographic method is broadly outlined. Step 708 calls for generating of CAD or other data, typically in digital form, representing a three-dimensional object to be formed by the system. This CAD data usually defines surfaces in polygon format, triangles with normals perpendicular to the planes of those triangles, e.g., for slope indications, being presently preferred. According to the teachings of this invention, design data may be modified from either a physical or mental embodiment of a desired object design for the purpose of processing the data during the build process to achieve curl balancing and to produce the desired object.

In Step 709, the PHIGS data or its equivalent is converted, in accordance with the invention, by a unique conversion system to a modified data base for driving the

stereolithography output system in forming three-dimensional objects. In this regard, information defining the object is specially processed to reduce stress, curl and distortion, and increase resolution, strength and accuracy of reproduction. In this step the regions requiring curl balancing are preferably determined and designated appropriately for proper handling when the material is transformed.

Step 710 in Fig. 45 calls for the generation of individual solid laminae representing cross-sections of a three-dimensional object to be formed. These generated solid lamina may differ, according to the present teaching, from the desired lamina of the three-dimensional object to achieve optimal curl balancing. Step 711 combines the successively formed adjacent laminae to form the desired three-dimensional object which has been programmed into the system for selective curing. Typically, steps 710 and 711 are simultaneously performed during layer formation.

Hence, the stereolithographic system of the present invention generates three-dimensional objects by creating a cross-sectional pattern of the object to be formed at a selected surface of a building material (e.g., an ultra-violet (UV), visible light, or infrared (IR) curable fluid-like material or the like) capable of altering its physical state in response to appropriate synergistic stimulation such as impinging radiation, electron beam or other particle bombardment, or applied chemicals such as by ink jet or spraying over a mask adjacent the fluid surface. Successive adjacent laminae, substantially representing corresponding successive adjacent cross-sections of the object except as modified according to the instant teachings, are automatically formed and integrated together to substantially provide a step-wise lamina or thin layer buildup of the object, whereby a three-dimensional object is formed and drawn from a substan-

tially planar or sheetlike surface of the medium during the forming process.

Step 712 calls for containing a fluid-like medium capable of solidification in response to prescribed reactive stimulation. Step 713 calls for application of that stimulation as a graphic pattern, in response to data output from the computer, at a designated surface to form thin, solid, individual layers at that surface, each successive layer representing an adjacent cross-section of a three-dimensional object to be produced. In the practical application of the invention, each lamina will be a thin lamina, but thick enough to be adequately cohesive in forming the cross-section and adhering to the adjacent laminae defining other cross-sections of the object being formed. According to the instant teaching, transformation of portions of layers of material may deviate from a substantially uniform layer by layer buildup, as necessary, to ensure adequate curl balancing and proper accuracy of the produced object.

Step 714 in Fig. 46 calls for superimposing successive adjacent layers or laminae on each other as they are formed, to integrate the various layers and define the desired three-dimensional object. In the normal practice of the invention, as the medium cures and solid material forms to define one lamina, that lamina is moved relatively away from the working surface of the medium and the next lamina is formed in the new layer of medium which replaces the previously formed lamina, so that each successive lamina is superimposed and integral with (by virtue of the adhesive properties of the cured medium) all of the other cross-sectional laminae.

The process of producing such cross-sectional laminae is repeated until the entire three-dimensional object has been formed. The object is then removed and the system is ready to produce another object which may be identical to the previous object or may be an entirely new object

formed by changing the program or object data controlling the stereolithographic system.

This invention provides a general means of ensuring that adjacent layers can be built to adhere to each other reliably, as well as providing a way to reduce or eliminate curling between layers and ultimate distortion in formed parts. Post cure distortion "creep" may also be reduced by the present invention due to higher levels of curing that accompany curl balancing.

The UV curable material used in the presently preferred embodiment of a working stereolithography system is XB5081 stereolithography resin, made by Ciba Geigy of Basal, Switzerland.

The light source for the presently preferred embodiment of a stereolithography system is typically a helium-cadmium ultraviolet laser emitting 325nM radiation such as the Model 4240-N HeCd Multimode Laser, made by Liconix of Sunnyvale, California.

Curling has generally been a problem in stereolithographic applications in the upward direction (upward curl) when transforming successive layers on top of one another. Upward curling is especially noticeable in downfacing regions of an object (features or areas of an object that overhang or extend away from the object, See Figs. 49 and 50) being formed because the layer forming the downfacing feature has no means of resisting upward forces when successive layers are adhered above it unless supports are included in the forming process. However, curling is also possible in a direction in the transformation plane of a layer such as when two horizontal vectors cure overlapping regions of material. Normal curl refers to curl of a first cured element of material in a direction towards a second cured element of material cured in contact with the first cured element. Likewise, reverse curl is curl in the opposite direction relative to normal curl; therefore, in the direction away from the second cured element. For example, when adhering

a second layer above and to a first lower layer, normal curl is in the upward direction while reverse curl will be in the downward direction. Although the present invention is primarily described in terms of normal curl being in the vertical upward direction and reverse curl being in the downward vertical direction the terms "normal curl" and "reverse curl" are just as applicable to, for example, horizontal curl in a right or left direction.

In order to understand the concept of curl-balancing it is helpful to first consider the concepts of downward curl in multiple layers, reverse curl in a single layer and the cure depth at which significant reverse curl will occur in a single layer. The concept of downward curl is similar to the concept of upward curl except that curling is induced in a layer of building material (e.g., photopolymer) in the downward direction. Thus, downward curl is a distortion that occurs when a lower layer of photopolymer resin or other similar building material is solidified in contact with a previously solidified upper layer of material. As the lower layer of material is transformed from a flowable state to a cohesive or solid state it undergoes a change in density. This change in density is usually an increase in density causing shrinkage of the material. As the lower layer of material shrinks at a greater rate than the material in the upper layer and simultaneously adheres to the previously formed upper layer, it can induce sufficient stress in the upper layer to distort it downward. In addition, for an exothermic material, this distortion may be enhanced by an increase in temperature and associated expansion during formation of the layer and, resulting contraction after cooling and adhesion.

The concept of inducing downward curl in multiple layers is similar to inducing reverse curl in a single layer. Significant reverse curl can be achieved in a single layer of material by curing the layer (from top to bottom) to a deep enough depth of cure such that the rate

of shrinkage near the top of a layer is smaller than that near the bottom. Initially, the shrinkage of material occurs either more rapidly near the top of the curing material or substantially at the same rate at the top and bottom of the curing material. As the cure depth of the layer increases, the rate of shrinkage of the layer begins to decrease near the top of the layer relative to the bottom of the layer. Eventually the layer will reach a thickness where the rate and extent of shrinkage near the bottom portion of the layer is substantially greater than the rate of shrinkage at the top portion of the layer thereby causing downward curl. For example, significant reverse curl will be achieved in a single layer of XB-5081 material, manufactured by Ciba Geigy of Basal, Switzerland at a cure depth of approximately 35 mils.

The cure depth at which significant reverse curl occurs in a single layer will vary depending upon the properties of the material being utilized. Reverse curl will occur when the rate of material shrinkage is occurring more rapidly at lower portions of a layer of transforming material than at higher portions of the layer such that the shrinking mass of material at the lower portions of the layer has sufficient modulus, as compared to that of the upper portions of the layer, to exert sufficient torque (stress) due to shrinking to cause a downward distortion (strain) of the layer.

Several important material properties can affect the cure depth at which significant reverse curl occurs. For example, when using a liquid photopolymer, that approximately absorbs synergistic stimulation according to Beer's Law, important properties to consider include, among others, the penetration depth of the material for a given type of synergistic stimulation, the extent of polymerization of a unit volume versus the exposure of that unit volume, the modulus of a unit volume for a given extent of polymerization, the density of a unit volume versus the extent of polymerization of that unit volume, and the

like. The cure depth at which reverse curl will occur can be theoretically determined from an appropriately derived and weighted function of these variables.

A critical property, or variable, used in determining the cure depth at which significant reverse curl occurs in a single layer is the penetration depth of the material. The penetration depth of the material dictates the amount of differential exposure that occurs at different volume elements at different levels below the surface of the material. Each time one penetration depth is traversed into a material that obeys Beer's Law, the exposure at that level decreases by 1/e where e is a constant equal to 2.7183. The smaller the penetration depth the higher the degree of differential exposure in a given depth of material and therefore the higher the likelihood of having differential curing as well.

Since reverse curl is based on differential shrinkage of the transforming material between the upper portions and lower portions of a layer, the rate of curing must be different between these portions; or else the shrinkage for the same rate of curing at different levels of cure must be different. With currently preferred photopolymers, measurements have indicated that shrinkage occurs substantially linearly with the rate of transformation. However, it has also been observed that with some materials especially when close to the point of maximum transformation, shrinkage for a given change in transformation (e.g., polymerization or curing) decreases. Additionally and most importantly, it has been observed that the rate of transformation per unit of exposure decreases as higher and higher levels of transformation are achieved. Therefore, it can be assumed that reverse curl is due predominately to the difference between the rate of transformation for different levels of transformation for a given exposure, thereby, resulting in different rates of transformation and corresponding rates of shrinkage at different levels of a material.

The rate of transformation is based on several criteria including the absorption properties and chemical properties of the particular material being cured. However, the two most important properties for present considerations are the exposure incident on a given volume element and the level of transformation that has already occurred on the given volume element. As the volume element is exposed, it begins to transform. As the material approaches the point of complete transformation the rate of transformation begin to slow. Eventually, when the point of complete transformation is reached, the rate of transformation will stop. Therefore, it is possible to have a faster rate of transformation in a unit volume that is receiving less exposure than in a unit volume that is receiving a much greater exposure but is closer to complete transformation. The same situation can occur when forming a layer from a material that obeys Beer's Law. As the upper portion of the layer approaches the point of complete transformation its transformation proceeds at a slower rate than the lower portion of the layer which remains relatively untransformed and therefore can have a higher rate of transformation. Therefore, in general, the smaller the penetration depth of a layer the thinner the cure depth necessary to begin to see the effects of reverse curl. Knowing the cure depth at which reverse curl begins to occur permits the selection of a layer thickness or, more specifically, a building layer thickness to use in building an object using the curl balancing technique. Generally, in standard applications, the building layer thickness remains constant for all the layers of the object being formed.

In the following discussion reference to a layer (e.g., balanced layer, core layer or balancing layer) or multiple layers and the like may refer to either an entire layer or merely a portion of a layer. Since curl balancing is generally applied to the layers above a down-facing feature and since down-facing features may only

encompass portions of a layer, only portions of layers need participate in a curl balancing technique.

The concept of curl balancing involves a relationship between a first layer (or group of layers) which acts as a balanced or core layer (e.g., a layer being curl balanced by another layer) with a second layer (or group of layers) which acts as a balancing layer (e.g., a layer that is balancing curl in another layer). The balancing layer induces upward and downward curl in the core layer in such a way that it eliminates or substantially reduces the final or net curl between the two layers. Although the balanced layer and balancing layer may not necessarily be formed using the building layer thickness the combination of their cure depths will result in a desired net cure depth or net thickness that may be a multiple of the building layer thickness (e.g., two building layers thick, three building layers thick and so forth). In addition to the balanced and balancing layers there are associated curl balancing parameters. Thus, the curl balancing parameters including the cure depth, layer thickness and exposure utilized with a given balanced layer are known as the balanced cure depth, balanced layer thickness and the balanced exposure, respectively, and those utilized with a given balancing layer are known as the balancing cure depth, balancing layer thickness and balancing exposure.

When two layers are being curl balanced together the embodiment is referred to as a two layer embodiment and the desired net cure thickness resulting from the combination of exposing the balancing and balanced layer is two layer thicknesses. When three layers are being balanced the embodiment is referred to as a three layer embodiment and the desired net cure thickness resulting from the combination of exposing the balancing and balancing layers are three layer thicknesses. Likewise, the concept is the same when we consider any higher order multilayer embodiment. However, when curl balancing a multilayer embodi-

ment a number of combinations are typically available for selecting a desired net thickness. For example, in a six layer embodiment it may be desireable to first balance two layers (e.g., the second and third layers) as a two layer embodiment having a desired net thickness of approximately two layers such that the lower surface of transformed material is above the desired lower level of the material to be transformed when processing of the six layers is complete. Subsequently, using the approximate two layer thickness as a balanced layer and the remaining layers as the balancing layer, the six layers may be cured to obtain a final desired net thickness of six layers and the desired placement of the lowest and highest transformed surfaces. The number of combinations available for a given embodiment will become evident upon review of the examples discussed herein.

The presently preferred material, XB 5081, has a penetration depth of approximately 7 mils (0.007 inches) and exhibits the onset of reverse curl at approximately 35 mils. This cure depth for reaching the onset of reverse curl makes this material useful for a two layer embodiment of curl balancing wherein the building layer thickness is approximately 20 mils. For example, this building layer thickness permits a first layer to be formed as a balanced layer (e.g., which may have a balanced cure depth of 15 mils instead of the 20 mil building layer thickness wherein transformation occurs from an upper level of the layer) and the successive layer to be cured as a balancing layer (e.g., which may have a balancing cure depth of 40 mils instead of the 20 mil building layer thickness wherein transformation begins from an upper level which is 20 mils above the upper level of the previous layer) to form a net cure thickness equal to a two layer thickness of 40 mils. Assuming the balanced and balancing layer thicknesses suggested in parenthesis are valid the two layers should be balanced to eliminate or substantially reduce the amount of curling that would result if the two

layers were merely formed as two successive 20 mil layers (including a minimal overcure associated with the second layer to assure adhesion).

In contrast, the presently preferred material (having a penetration depth of 7 mils) would not be a satisfactory material for curl balancing with a two layer embodiment when using a building layer thickness of 5 mils. If a two layer embodiment of curl balancing were desired with 5 mil layers, it would be beneficial to use a material having a penetration depth of 1-3 mils.

Although the curl balancing concepts are similar for any multilayer embodiment the present invention will be initially addressed in terms of a two layer curl balancing embodiment. In considering a curl balancing embodiment, the cure depths or exposures of each layer must be selected appropriately to accomplish two goals including: 1) balancing the curl in a two layer combination and 2) transforming the desired net cure thickness as measured from the upper surface of the upper layer. Curl balancing is achieved by curing the balancing layer deep enough into the balanced layer or beyond the lower level of cure of the balanced layer so that upward and downward curl are balanced and net curl is eliminated or substantially reduced.

Also, it should be noted that as the balancing cure depth is increased, the width of the balancing layer becomes wider and will tend to distort the shape of the final object. Therefore, the cure width of the balancing and other layers must be adjusted through a cure width compensation means several of which are known in the art and disclosed in Section 1.

The net cure depth thickness is achieved using one of three methods: 1) if the balancing cure depth of the balancing layer extends beyond the lower limit of the balanced cure depth of the balanced layer, the balancing cure depth and therefore its exposure is used to achieve the net cure thickness; 2) if the net cure thickness is

substantially achieved due to the combined exposures of the balancing and balanced layers, then the combination of exposures must be considered in achieving the desired cure depth as well as achieving curl balancing; and 3) if the net cure thickness is substantially determined by the balanced cure depth of the balanced layer then the exposure of the balanced layer must be selected to give substantially a cure depth of one layer thickness. As a case 1 example, if one is building with a material that obeys Beer's Law and significant single layer reverse curl sets in with cure depths somewhat less than two layer thicknesses, it may be desireable to plan to cure the balancing layer to a depth of a two layer thickness and to select a cure depth for the balanced layer at something less than a one layer thickness so that the downward curl balances the upward curl. In any of the three cases, it may be necessary to utilize theory to predict the desired exposures, iterative processes based on a selection of initial exposures to determine whether the process eventually converges to yield exposures that achieve curl balancing and the desired cure thicknesses, or experimental techniques for determining the necessary exposures that achieve the desired goal.

For given material and layer thickness combinations and object geometries that have a thickness greater than two layers, curl balancing using a two layer embodiment may be inappropriate and a multilayer embodiment having N layers (where N is greater than two) may prove more suitable. For a two layer embodiment of curl balancing to be effective any additional layers adhered to the two layers must not induce significant curl in the two layers. If a relatively weak material is used, curl balancing may be achieved with two layers but a third or other higher level layer may reintroduce upward curl in the combined layers. In a multilayer embodiment, curl balancing may be achieved by exposing the material from two different levels of the object although the requirement of a two

layer net cure thickness would be replaced by a N-layer net cure thickness; or in a multilayer embodiment, the curl balancing and desired net cure thickness can be achieved by exposing the material at more than two levels of the object.

For object geometries that are only two layers thick and for which no appropriate exposure combinations can be found to achieve curl balancing, it is desirable to do some special processing of the two layer thick region. When curl balancing using a two layer embodiment cannot be achieved for object geometries that are only two layers thick, it is reasonable to assume that the material is capable of forming a single layer of material equal to a two layer thickness without the onset of significant reverse curl. That is, the two layers are treated as a single layer and synergistic stimulation is applied to expose both layers of the region from the upper surface of the higher of the two layers such that the resulting cure depth is equivalent to two layer thicknesses. In other words, the balanced layer is omitted (e.g., has a zero balanced cure depth) and the balancing layer is cured to form a desired net thickness of two layer thicknesses.

In further considering case 1 above, an upper portion of the balancing layer forms above the core layer inducing upward curl of the core layer; and, a lower portion of the balancing layer forms below the core layer inducing downward curl of the core layer. Curl balancing occurs when the upward and downward curl of the core layer balances out to a point where curl is substantially reduced or eliminated. This concept is best explained in reference to the models illustrated in Figs. 47 and 47a.

Fig. 47 illustrates a model of two stereolithographically formed layers of an object. The first layer is supported by an appropriate means (not shown). The two layers are successively cured to each other such that a first layer L_A having a building layer thickness 1 adheres to a second layer L_B also having a building layer

thickness l. That is, after the first layer L_A is cured the SLA lowers the elevator platform a distance equal to a layer thickness l and the second layer L_B is cured to a cure depth d which includes an overcure d_o to ensure adhesion to the first layer L_A. As indicated by the dotted line, the first layer L_A will curl upward as the second layer L_B shrinks. Using the curl balancing concept the two layers in Fig. 47 can be cured in relation to each other such that the distortion caused by curling is substantially reduced or eliminated as illustrated in Fig. 47a.

Turning in detail to Fig. 47a, a second model of two stereolithographically formed layers of the same object as in Fig. 47 is illustrated except that the object in Fig. 47a is formed using curl balancing. The building layer thicknesses in Fig. 47a are also equal to l. The first layer L_A is selected as the balanced layer L_{BD} and the second layer is selected as the balancing layer L_{BG}. A cured portion of the first layer L_A is cured to a cure depth d_A which is also the balanced cure depth d_{BD}. After the first layer L_A is cured to a cure depth d_{BD} (e.g., where $d_{BD} < l$) the second layer L_B is cured to a cure depth d_B which is the balancing cure depth d_{BG} to form a layer thickness equal to 2*l (e.g., where $d_{BG} > l$). In other words, the second layer L_B (balancing layer L_{BG}) overcures the entire first layer L_A (balanced layer L_{BD}) such that upward curl of the first layer L_A caused by the second layer L_B is substantially negated by downward curl of L_A caused by L_B. Thus, the second layer L_B is comprised of an upper region L_{Bu} above the previously cured portion of the first layer L_A and a lower region L_{BL} below the previously cured portion of the first layer L_A. As the upper region L_{Bu} shrinks and adheres in relation to the first layer L_A it tends to create an upward torque on the first layer L_A inducing upward curl thereon. Similarly, as the lower region L_{BL} shrinks and adheres in relation to the cured portion of the first layer L_A it tends to create a downward

torque on the cured portion of the first layer L_A inducing downward curl thereon. By balancing or playing the upward torque and downward torque on this cured portion of the first layer L_A against each other the net curl of the layers can be substantially reduced or eliminated.

This description applies to a case 1 situation. Therefore, the balanced exposure and balanced cure depth of the balanced layer are specified so as to be balanced by the balancing layer which is given an appropriate balancing exposure to cause a net cure depth equal to a two layer thickness. In this case, a material that obeys or approximates Beer's Law is used. The appropriate balancing exposure is substantially that required to achieve a balancing cure depth of two layer thicknesses regardless of whether there was a previously cured region L_A. In a case 2 situation, a partially bleaching material is used. The appropriate balancing exposure of the balancing layer L_B has to take into account the previously exposed region L_A due to the change in absorption properties of the material due to the previous exposure.

As described earlier, the value or magnitude of the curl balancing parameters needed for curing a balanced layer L_{BD} in relation to a balancing layer L_{BG} are determined primarily by the material properties of the photopolymer being used, the synergistic stimulation, and the layer thickness. For a photopolymer material and synergistic stimulation combination, a number of acceptable building layer thicknesses can be utilized. A range of these layer thicknesses can be utilized in the curl balancing process and for each building layer thickness 1 in each material there is a range of values for the curl balancing parameters that can be utilized to substantially reduce or eliminate curling. This range of values and appropriate exposure parameters are designated as the optimum curl balancing parameters and are stored in the controlling computer of the SLA for each photopolymer material utilized by the SLA.

The optimum curl balancing parameters can be determined both empirically and theoretically and involve knowledge relating to the range of cure depths or single thicknesses of a single layer of a photopolymer wherein significant reverse curl begins to occur.

To empirically determine optimum curl balancing parameters a series of test parts may be formed using predetermined or given parameters including the balanced layer thickness l_{BD}, balancing layer thickness l_{BG}, and balanced cure depth d_{BD}. Test parts are then built with varying balancing cure depths d_{BG} (e.g., balancing cure depths equal to $l_{BG}...1.5l_{BG}...2l_{BG}$) applied to each test part. For example, for a building layer thickness l, a first balanced layer L_{BD1} is cured to a support having a specified or predetermined balanced layer thickness l_{BD1} having a specified or predetermined balanced cure depth d_{BD1}. A specified or predetermined balancing layer L_{BG} having a balancing layer thickness l_{BG} is then cured and adhered to the first balanced layer L_{BD} using a balancing cure depth d_{BG1} which is the first of a range of balancing cure depths $d_{BG(x)}$. Similarly, additional series of test parts may successively be formed using the different predetermined values l_{BD}, d_{BD}, and l_{BG} while progressively or incrementally changing the balancing cure depth d_{BG} (x ... x_n). Eventually, from the range of balancing cure depths d_{BG} (x_1 ...x_n) for the various values l_{BD}, d_{BD} and l_{BG} one can extract the optimum range of balancing cure depths for achieving optimum curl balancing results for the various values l_{BD}, d_{BD} and l_{BG}. If desired balancing layer thickness l_{BG} and balanced layer thickness l_{BD} are known (for example, both being 5 mils or both being 20 mils or one being 10 mils and the other being 5 mils) then one must only vary the balancing cure depth and balanced cure depth, by varying the balancing exposure and balanced exposure respectively, and determine the appropriate values that yield the proper net cure thickness and that demonstrate adequate reduction in curl. These appropriate

cure parameters (i.e. depth relationships or exposure relationships) can then be applied during the building process to the appropriately determined layers or portions of layers of a part that is being built by the techniques of stereolithography. These regions can be determined by a SLICE type program or the like as disclosed in U.S. Patent Application 331,644 or concurrently filed U.S. Patent Application Serial No. 07/606,191 entitled "Boolean Layer Comparison Slice". If not already done, a similar approach may be used for determining other curl balancing parameters. The procedure will be similar except that other curl balancing parameters will be extracted from the data.

The cure depths for curl balancing can also be theoretically determined based on known material properties such as critical exposure, penetration depth, extent of polymerization versus exposure, shrinkage versus extent of polymerization, modulus versus shrinkage or polymerization, and extent of polymerization of the balanced layer.

Turning in detail to Fig. 48, an object is shown which is to undergo stereolithographic building utilizing the curl balancing method and apparatus. For simplicity and as illustrated in Figs. 49a-49d, the object is comprised of four layers L_1, L_2, L_3 and L_4 having a fixed building layer thickness 1.

Each layer is comprised of a surface that faces upward and a surface that faces downward. If the lower surface, or portion of the lower surface of a layer is not bounded from below by another adjacent layer then it is defined as a downfacing region DF. For example, in Figs. 49a-49d, the first layer L_1 has a downfacing region DF_1 because it is not adhered to any layer below it (except for a support structure not shown). Similarly, the second layer L_2 is comprised of a downfacing region DF_2 which extends out past the first layer L_1 and, therefore, is not bounded by a lower layer.

Once each of the downfacing surfaces or regions is identified, these downfacing regions on their respective layers are selected as potential curl balance layers PCB. As illustrated in Figs. 49a-49d, there are two downfacing regions in the object including downfacing region DF_1 including the entire first layer L_1 and downfacing region DF_2 including the portions of the second layer L_2 overhanging the first layer L_1.

Once the downfacing layers or regions have been identified and categorized as potential curl balance layers PCB (e.g., DF_1: PCB_1, and DF_2: PCB_2) they are further categorized to determine which downfacing regions have a second layer above them. These downfacing regions are then designated curl balanced layers or regions L_{BD}. Thus, downfacing region DF_2 is selected as a curl balanced region L_{BD2}. The portion of the third layer L_3 above the curl balanced region L_{BD2} is designated as a curl balancing layer or region L_{BG3}.

Since downfacing region DF_1 is the first layer L_1 of an object it will be cured to a support and it may not be necessary to designate it as a curl balanced region. Since the support is secured to the elevator platform (not shown) this layer can adequately resist curling so that curl balancing will generally not be necessary. However, if curl balancing is desired on this layer, the layer may be treated as a curl balanced layer L_{BD1} (not shown) and the portion of layer 2 above the L_{BD1} (not shown) would be treated as a curl balancing region L_{BG2} (not shown).

Supports are required when building objects using stereolithography for several reasons. First, as with the first layer L_1, supports are necessary to attach or secure the base of an object being built to the elevator platform. Second, supports may be built to attach or secure any unsupported or downfacing areas of an object such as downfacing region DF_2 being built to protect that area of the object from damage that may occur during the part building process. For example, the objects may

undergo a significant amount of upward and downward motion relative to the building material during the coating process. Therefore, the object and, most notably the downfacing region DF_2, will be subjected to forces that are capable of breaking, bending, distorting, or simply misplacing unsupported areas of the object unless they are properly secured. Third, supports are required to restrain or rigidly support regions of an object that are likely to distort due to curl. Each of the three situations mentioned requires a substantial amount of support. However, the third situation is especially significant and often requires much more design consideration than other supports. The first two situations can be generally and adequately handled by roughly placed generic supports. However, for example, the corners of an object are prime targets for curl and, therefore, typically require specifically placed supports to prevent them from distorting. However, the location and orientation of the corners are object dependent making the design of the supports difficult. As a result, the design of supports to restrain areas such as corners likely to curl is a time consuming process. Through the method and apparatus of the present invention, curl is reduced thereby reducing the need for supports. Thus, the file sizes required, CAD design time and part building time are also reduced.

Once the various layers and regions have been identified or categorized the three-dimensional object in Figs. 49a-49d is built layer by layer using standard stereolithographic exposures except in the regions designated as the curl balanced layer region L_{BD2} and the curl balancing layer region L_{BG3}. The new exposures associated with the curl balanced layer region L_{BD2} and curl balancing layer region L_{BG3} are predetermined based upon previously stored information of optimal curl balancing parameters as well as other information pertaining to the

material being used in connection with the given building layer thicknesses l_{BG} and l_{BD}.

When building the object in Figs. 49a-49d, a support for the object is formed attached to the elevator platform. The layers L_1, L_2, L_3 and L_4 are then successively formed adhering through each other to the support. Each layer is then cured to a building layer thickness l, or a building layer thickness plus a desired over cure, according to standard stereolithographic procedures unless the region being cured has been designated for curl balancing. Generally, the wavelength applied to each layer remains constant throughout the process of curing the layers whether for a standard layer or a layer designated for curl balancing and the exposure is varied in order to achieve the various cure depths.

However, wavelengths of radiation may be utilized advantageously when applied to curl balancing. For example, multiple wavelengths can be applied to achieve multiple or variable penetration depths in a single material to transform different building layer thicknesses. Similarly, variable wavelengths of radiation may be utilized for transforming the curl balancing layer and the balanced layer. That is, it may be advantageous to use two different wavelengths including one having a shorter penetration depth to transform the balanced layer and a second having a longer penetration depth to transform the balancing layer.

Assuming in Fig. 49a-49d that the wavelength remains constant, the first layer L_1 is cured to a depth d equal to the layer thickness l. Although not preferred, but commonly done, it may also be given an overcure depth sufficient to adhere the first layer L_1 to the elevator platform supports. The preferred approach is to give the first layer L_1 a layer thickness cure depth and to ensure adhesion to the supports by building at least one additional layer of supports (including an overcure) in association with at least the first layer. The elevator

platform is then relatively lowered a net incremental distance equal to the layer thickness 1 to permit the second layer L_2 to be coated and cured.

The second layer L_2 is broken down into two regions that require different exposures including a first region L_{2A} and a second region designated the curl balanced layer region L_{BD2}. Therefore, the second layer L_2 is cured using a standard stereolithographic cure depth and exposure for the first region L_{2A} and a balanced layer exposure and balanced cure depth d_{BD} for the balanced layer region L_{BD2}. Therefore, the first region L_{2A} of the second layer L_2 is cured to a depth d equal to the layer thickness l_{BD} (where l_{BD} =1) plus an overcure depth d_o sufficient to adhere the second layer L_2 to the first layer L_1. However, when the synergistic stimulation cures the curl balanced layer region L_{BD2} the exposure changes from an exposure calculated to transform material to a cure depth d to a balanced exposure calculated to transform material to a balanced cure depth d_{BD} which may be less than or equal to the layer thickness 1. Several examples of the various combinations of balanced cure depths d_{BD} and balancing cure depths d_{BG} are shown in Figs. 49a through 49d. It should be noted that the curl balanced layer region L_{BD2} can be supported by webs or the like. The curl balanced layer region L_{BD2} is less susceptible to curl but it may be relatively weak due to a possible shallow cure depth. Therefore, a generic support structure might be helpful.

The third layer L_3 is also broken down into two regions including a first standard region L_{3A} and a second region which is designated the curl balancing layer region L_{BG3}. The first region L_{3A} is cured as a standard layer having a layer thickness l_{BG} (where l_{BG} =1) and a cure depth d equal to the layer thickness l_{BG} plus an appropriate overcure depth d_o (if necessary) to adhere the first region L_{3A} to the second layer L_2. When the laser or the like cures the curl balancing layer region L_{BG3} the exposure changes to an appropriate exposure to increase the cure

depth d to a balancing cure depth d_{BG} which, as shown in the examples of Figs. 49a through 49d, may be less than or equal to the thickness of the third layer L_3 plus the second layer L_2 ($d_{BG} \leq 2l$). It is, however, more than the exposure which was used for merely adhesion purposes on L_{3A}.

Turning in detail to Figs. 49a-49d, one of a variety of different balancing cure depths and balanced cure depths may be required and will depend upon the properties of the material and the building layer thickness being utilized. In Fig. 49a, curl balancing is achieved using a balanced cure depth d_{BD} less than the building layer thickness l and a balancing cure depth d_{BG} equal to the balancing layer thickness l_{BG} plus the balanced layer thickness l_{BD} which is twice the fixed building layer thickness ($d_{BG} = l_{BG} + l_{BD} = 2l$).

In Fig. 49b, curl balancing is achieved using a balanced cure depth d_{BD} equal the layer thickness l and a balancing cure depth d_{BG} equal to twice the building layer thickness 2l.

In Fig. 49c, curl balancing is achieved using a balanced cure depth d_{BD} equal to the layer thickness l and a balancing cure depth d_{BG} greater than one building layer thickness l plus a standard adhesion overcure thickness d_o or ($l + d_o$) for the given material but less than twice the building layer thickness 2l.

In Fig. 49d, curl balancing is achieved using a balanced cure depth d_{BD} less than one building layer thickness l and a balancing cure depth d_{BG} greater than one layer thickness l but less than twice the building layer thickness 2l wherein the combined exposures result in a net cure thickness equal to 2l.

Finally, the fourth layer L_4 is cured as a standard layer to a cure depth d equal to a layer thickness l plus a sufficient overcure d_o to adhere the fourth layer L_4 to the third layer L_3. It should be noted that depending on the complexity of a three dimensional object there can be

many curl balancing regions with respective balancing and balanced layers. In addition, different portions of the same layer or cross-section of an object can serve as both balancing layers and as balanced layers. A simple example is illustrated in Fig. 50 which shows a three dimensional figure or object broken down into ten cross-sections or layers L_1-L_{10}. There are two curl balancing regions CB_1 and CB_2. The first curl balancing region CB_1, has a balanced layer L_{BD4} on a portion of layer L_4 and a balancing layer L_{BG5} on a portion 5_A of layer L_5. The second curl balancing region CB_2 has a balanced layer L_{BD5} on a portion 5_C of layer L_5 and a balancing layer L_{BG6} on a portion of layer L_6. Thus, the fifth layer L_5 has a portion 5_A which serves as a balancing layer, a portion 5_B which serves as a standard layer and a portion 5_C which serves as a balanced layer.

A second embodiment of the present invention permits curl balancing of three or more layers at one time. Although applicable to any layer thickness, this embodiment is especially useful when the building layer thickness 1 being utilized is relatively thin. This advantage stems from the fact that thin layers are usually relatively weak; and additionally from the situation wherein the material and synergistic stimulation is inappropriately combined to achieve curl balancing in association with a two layer embodiment. Even if the two layer embodiment can be implemented, some balanced layers may still have a combined strength which is relatively weak and therefore subject to curl when a third or higher layer is transformed above them using standard techniques. Therefore, it is more appropriate to apply a curl balancing technique which will result in a net structure which is more than two layers thick and will resist any distorting stresses which arise from subsequent standard applications of additional layers.

Turning in detail to Fig. 51, an object is illustrated having seven layers L_1-L_7 including a curl balancing region generally designated CB. The curl

balancing region CB is a multilayer structure or, more specifically, a three layer structure which will be transformed according to a three layer curl balancing embodiment. This embodiment is shown in Figs. 51A and 3-9B which illustrate sample methods of transforming a three layer embodiment to achieve curl balancing. Since the method for building standard layers and regions has been addressed the three layer embodiment discussion is limited to the curl balancing region CB. For simplicity, the portions of layers three through five L_3-L_5 illustrated in the curl balancing region CB will be treated as complete layers.

There are several methods for curl balancing a three layer embodiment all of which require identifying the respective balancing and balanced layers and their associated cure depths and exposures. As illustrated in Fig. 51a, if a two layer embodiment would be strong enough to resist curl, a simple solution for curl balancing the three layer region CB would be to curl balance the third layer L_3 with the fourth layer L_4 using any of the methods described in the first embodiment (e.g., using a two layer embodiment) and then cure the fifth layer L_5 on top of the fourth layer L_4 (or balancing layer L_{BG4}) to a standard cure depth d_5 with a sufficient overcure d_o to adhere the fifth layer L_5.

Another approach, illustrated in Fig. 51b, would involve by-passing any initial transformation of the third layer L_3 and treating the fourth layer L_4 as the curl balanced layer and giving it a cure depth of d_{BD4} (where $d_{BD4} \leq 21$) and treating the fifth layer L_5 as the curl balancing region and giving it a cure depth of d_{BG5} where D_{BG5} =31). Alternatively, as opposed to transforming a curl balanced or curl balancing portion of the third and fourth layers L_3 and L_4, both these layers can be by-passed and the fifth layer L_5 can be cured as a single layer to a cure depth equal to a three-layer thickness (not shown).

Referring to Fig. 51c, another alternative depending on the given curl balancing parameters is to curl balance region CB applying the curl balancing technique to all three layers. Thus, the third layer L_3 is initially designated the balanced layer L_{BD3} having a balanced cure depth d_{BD3} and is cured in relation to the fourth layer L_4 which is initially designated the balancing layer L_{BG4} having a balancing cure depth d_{BG4}. Depending on the circumstances the two layers may be substantially curl balanced but have a net cure depth that does not match the desired cure depth. This combined layer will now be curl balanced by exposure of the fifth layer L_5 and is therefore designated as a balanced layer $L(L_{BG4}\ L_{BD3})_{BD}$. The fifth layer L_5 is therefore designated as a balancing layer L_{BG5} and cured to a balancing depth d_{BG5} (e.g., equal to three layer thicknesses) in relation to the curl balanced layer $L(L_{BG4}\ L_{BD3})_{BD}$ such that the three layers are now curl balanced.

A third embodiment is shown in Fig. 52, which illustrates an object similar to the object shown in Figs. 49 and 51 except that it is divided into sixteen layers. The initial considerations for identifying the various regions are the same as described for Figs. 49 and 51. Thus, the seventh layer L_7 will have a downfacing surface DF_7. Since there are six layers including the seventh through twelfth layers L_7-L_{12} above the downfacing region DF_7 a variety of curl balancing embodiments are possible. In this example a four layer embodiment of curl balancing is being used.

Curl balancing four layers requires defining the curl balanced layer L_{BD} and the curl balancing layer L_{BG}. Of course, as illustrated in the earlier embodiments, the greater the number of layers involved in a multilayer curl balancing embodiment, the greater the number of curl balancing options that are available. Since the procedure for curl balancing is the same for all embodiments (aside from determining the balanced layers and balancing layers)

a number of these variations will merely be identified for the four layer embodiment to illustrate the various combinations.

The first obvious curl balancing variation would be to utilize an embodiment having fewer than four layers if the curl balanced layers are strong enough to resist curl when another layer is successively applied. For example, if a three-layer embodiment produces a strong enough structure to resist curl when a fourth layer is transformed (using standard techniques) above and to the previously transformed three-layer thickness of material then any of the techniques discussed with respect to Fig. 51 would become viable curl balancing methods for the object in Fig. 52. That is, layers L_7 through L_9 can be curl balanced using one of the variations for curl balancing a three-layer embodiment and then the tenth layer L_{10} can be transformed to the ninth layer L_9. Similarly, a two-layer embodiment curl balancing technique can be applied, if adequate, to balance the seventh layer L_7 with the eighth layer L_8 and then, use standard techniques to transform the ninth layer L_9 and the tenth layer L_{10}. Other approaches exist as well which utilize a combination of curl balancing and other curl reduction techniques.

Specifically addressing the four-layer embodiment, the ninth layer can be designated the balanced layer L_{BD9} and cured anywhere from a balanced cure depth d_{BD9} of less than 1 up to 31 (e.g., $0 < d_{BD9} \leq 31$). The layer L_{10} will then be the balancing layer L_{BG10} having a balancing cure depth d_{BG10} which might range from a value greater than 21 up to 41 (e.g., $21 < d_{BG10} \leq 41$) depending, of course, on the curl balancing parameters as discussed above. Using these guidelines, the various layers would be identified and input into the SLA and transformation would begin.

The first portions (non-curl balancing portions) of the seventh through ninth layers L_7-L_9 are successively cured using standard stereolithographic procedures and

parameters. In terms of a scanning laser, the overhanging or downfacing regions of layer seven and the overlapping region of layer eight are not addressed until the laser reaches layer nine L_9. In other words, in this approach the downfacing portion of layer seven L_7 as well as the portion of layer eight L_8 above the down-facing portion of layer seven L_7 will not be transformed in association with transformation of the non-curl balancing portions of layers seven or eight which are cured using standard exposures. Initially, the first portion of the ninth layer L_9 is cured using a standard exposure. The exposure then changes to a balanced exposure to cure the balanced layer L_{BD9} to a balanced cure depth d_{BD9}. The laser will then cure the first (non-curl balancing portion) portions of the tenth layer using standard stereolithographic exposures until it reaches the beginning of the balancing layer L_{BG10}. The laser then changes to a curl balancing exposure to cure a balancing layer L_{BG10} to a balancing cure depth d_{BG10} to obtain a balancing cure depth d_{BG10} which for this example, in the tradition of Fig. 49, is equal to the combined layer thickness of layers seven through ten (i.e. $l_7 + l_8 + l_9 + l_{10} = 41$). The remaining layers are then cured using standard stereolithograhic procedures or curl balancing procedures as needed until the object is completely built. This assumes, of course, that the four layer embodiment is strong enough to resist curl caused by the eleventh and twelfth layers L_{11} and L_{12}. Other curl balancing embodiments, of course, are available and should be evident to those skilled in the art.

It is further noted that although the description of the curl balancing technique is presented with respect to upward vertical curl it is also applicable to other forms of curl including downward curl when a part is being built upside down, sideways curl when a part is being built sideways, and various forms of horizontal curl or curl in a plane perpendicular to the building axis when lines of transformed material are formed in contact with each other

on a single layer. For example, as illustrated in Fig. 53 which shows the top view of a vertical layer, a core or balanced line A_{BD} is transformed using a tightly focused beam of synergistic stimulation. Subsequently, a balancing line B_{BG} is transformed using a less focused beam thereby resulting in a transformed balancing line having a first portion B_{BG1} and a second portion B_{BG2} that balances potential horizontal curl as indicated by the dashed lines. Alternatively, as illustrated in Fig. 54, alternative sides of the balanced line A_{BD} can be successively transformed as indicated by the transformed areas 1, 2, 3, and 4 to form a balancing line B_{BG}. Thus, alternative sides of the balanced line A_{BD} will be successively transformed until the end of the balancing layer B_{BG} is reached and the last area N is transformed.

As described herein before, a single material and synergistic stimulation source combination can be used to effectively practice curl balancing even when a variety of layer thicknesses are used in forming objects. This material and synergistic stimulation source combination may be used in a two layer embodiment or a multiple layer embodiment to most effectively eliminate curl for a given layer thickness. Alternatively, the range of applicability of a single material to a particular embodiment (e.g., two layer embodiment) can be substantially increased by utilizing different penetration depths of the synergistic stimulation with the material. For example, a given UV curable material may have a longer penetration depth with one wavelength and shorter penetration depth with another wavelength. The longer penetration depth can be applied to two layer embodiments having relatively thick layers whereas, the shorter penetration depths can be applied to two layer embodiments having relatively thinner layers. Thus, if a given material has a penetration depth of 7 mils with a first wavelength and a penetration depth of 1-3 mils with a second wavelength, this material and first wavelength may

be effectively applied to 20 mil layer thicknesses whereas the material and second wavelength may be effectively applied to 5 or 10 mil layer thicknesses.

Additionally, other embodiments may be developed wherein the balanced and balancing layers may be cured using different penetration depths. For example, the balanced layer may be cured with shorter penetration depth radiation to make it more rigid whereas the balancing layer may be cured using the longer penetration depth radiation to more quickly obtain the desired cure depth (as long as the curl balancing effect remains). The determination of appropriate wavelengths and cure parameters can readily be obtained by the previously discussed empirical or theoretical methods, wherein the penetration depths will also be one of the variables.

These curl balancing techniques may be effectively applied to eliminate or reduce curl when stereolithographically building a part. Up to this point the curl balancing techniques have been described as being implemented into the stereolithography process while slicing the three-dimensional object into layers. It is, however, important to realize that the methods of curl balancing can be implemented from a variety of points in the process.

An object design having a particular shape and size may be represented by a physical design such as data on a CAD system, a physical model or a mental image. This initial design generally is not based on the method that will be used to physically produce or reproduce the object and, therefore, it may be modified for purposes of production. For example, the design may be modified so that all vertical features are thicker than the building layer thickness to be used in forming the object. In terms of the present invention the original design may be modified for implementation of curl balancing methods. For example, the down-facing features to be curl balanced may be moved up one or more layers above the desired

locations and an equivalent feature may be created one layer above the modified down-facing feature position. Then the modified down-facing feature can be given a balanced layer exposure and cure depth while the equivalent feature can be given a balancing layer exposure and cure depth wherein the combined exposures would lead to a cure depth which results in the down-facing feature being placed at the proper vertical position of the original object design. Such modifications are to be included in the methods and apparatus of the present invention.

In the stereolithography process the object design may be modified into a building design and thereafter sliced into individual cross-sections which will be used to form the object. Modifications during slicing or after slicing to the cross-sections can be made for the purpose of curl balancing. Examples of such modifications have been described previously. These modifications may be performed by a computer or the like programmed to introduce desired changes or separation of curl balancing regions and therefore fall within the scope of the method and apparatus of the present invention.

After formation of the cross-sectional data or object parameter information which corresponds to the object to be formed (with or without deviations for curl balancing from an original data set), the object can be stereolithographically produced by a building program. The data or parameter information can be further modified or manipulated to result in curl balancing methods of formation of the object. Such manipulation can include the specification and control of exposure parameters, or even the determination of regions to treat as curl balanced or curl balancing regions.

In summary, the scope of the curl balancing methods of the present invention include modifications to the original object design (i.e. modifications from a desired object configuration) through modifications during the building process of the object. The scope of the curl

balancing apparatus of the present invention include apparatus that modify an original physical (CAD design or the like) object design through apparatus that build the object using curl balancing parameters.

Description of the Preferred Embodiments

Section 4: Improved Surface Resolution in Three-Dimensional Objects By Inclusion of Thin Fill Layers

The preferred embodiments of the subject invention distinguish between filling in surface discontinuities of up-facing features and filling those of down-facing features. Up and down-facing features are described in more detail in WO 89/10256. Briefly, in an object built with a plurality of structural layers, the term "up-facing" refers to a region on the object surface bounded by an extension region on an upper surface of a second structural layer and an end of an adjacent first structural layer situated above the second structural layer where an end of the second structural layer extends beyond an end of the first structural layer by the extension region. The term "down-facing" refers to a region on the object surface bounded by an extension region on a lower surface of a second structural layer, and an end of an adjacent first structural layer situated below the second structural layer, where an end of the second structural layer extends beyond an end of the first structural layer by the extension region. The above definitions of down-facing and up-facing regions are suited for the needs of this application; however, in general, any region of a layer which is not bounded from below is a down-facing region, similarly for any region of a layer which is not bounded from above is an up-facing region.

The treatment of surface discontinuities of down-facing features will be addressed first. Figs. 56a through 56e all illustrate different methods of forming fill layers that fill surface discontinuities at a

down-facing feature. In each of these figures, like elements are referred to with like numerals. In particular, the shorter first structural layer is referenced with numeral 806, the second structural layer with numeral 805, the ends of the first and second layers by the numerals 806' and 805', respectively, and the extension region on the lower surface of the second layer is referenced with identifying numeral 805". The surface discontinuity comprises a deviation between a down-facing region of the object surface and an envelope of an object representation. The down-facing region of the object surface is bounded by the extension region 805" of the second layer, and the edge 806' of the first layer. The deviation is, in turn, bounded by this down-facing region of the object surface and the envelope 810 of the object representation.

An aspect of the subject invention is the use of thin fill layers to reduce a surface discontinuity. The thin fill layers which have been added to reduce the surface discontinuity are referenced with numerals 807a, 807b, and 807c. Each of the layers shown in the figures, both structural and fill layers, are formed in a particular order, and the order in which each layer is built is indicated by a circled number corresponding to that layer.

In Fig. 56a, a first example is illustrated. In this example, structural layer 806 is formed first by selective exposure of material at a working surface to synergistic stimulation when the working surface of the material is located at level L1. According to the principles of stereolithography, the material is of the type that is flowable, and which is capable of selective physical transformation upon selective exposure to the synergistic stimulation. Layer 806 has a thickness and the required exposure to achieve a given thickness using typical materials such as photopolymers is described in more detail in WO 89/10256.

Next fill layer 807a is formed lengthwise relative to the working surface, by exposure of material situated at the working surface. Also, layer 807a is formed while the working surface is at level L1. However, layer 807a is formed with a thickness less than the thickness of layer 806 by appropriately reduced exposure of material at the working surface to the synergistic stimulation. In this example, layer 807a has a first end 807a' which adheres to end 806' through the natural adhesive properties of the material upon transformation.

Layer 807a also has a second end 807a" which abuts against envelope 810 of the object representation, as shown.

Next, while the working surface is still at L1, layer 807b is formed lengthwise relative to the working surface, below the lower surface 807a'" of layer 807a, by exposing at least in part the upper surface 807a"" of layer 807a at a sufficient exposure to expose and transform material below the lower surface 807a'" of layer 807a. As shown, upon formation, layer 807b has an upper surface which is adhered at least in part to the lower surface of layer 807a, and a first end which is adhered at least in part to the end 806' of the first structural layer, through the natural adhesive properties of the material upon transformation, as described previously. The layer also has a second end which abuts at least in part against the envelope 810.

The formation of layer 807b illustrates a significant aspect of the method of Fig. 56a, which is the formation of fill layers, such as layer 807b, below other fill layers without moving the partially-formed part relative to the working surface.

As explained in more detail in WO 89/10811, the incremental exposure required to form layer 807b can be determined by the exposure already applied to form layer 807a, and by the required thickness of layer 807b.

Next, layer 807c is formed lengthwise, in a similar manner to layer 807b, by transforming material situated below the lower surface of layer 807b, again while the working surface is at L1. Regarding the exposure required to form layer 807c, this will depend on the exposures already applied to form layers 807a and 807b, respectively. Again, the thickness of layer 807c will be less than the thickness of layer 806. Also, upon formation, the upper surface of layer 807c will be adhered to the lower surface of layer 807b, and the first end of layer 807c will be adhered to the end 806' of the first structural layer, similar to the manner described previously for layers 807a and 807b. The second end of layer 807b abuts the envelope 810 in the same manner as described above with respect to layers 807a and 807b.

Note that layers 806, 807a, 807b and 807c are all formed while the working surface remains at L1. Consequently, if the means for causing relative movement between the partially-formed part is a platform coupled to a Z-stage elevator then the platform and elevator need not be moved throughout the formation of these layers.

Next, the partially formed part including the upper surfaces of layer 806 and layer 807a are lowered relative to the working surface, resulting in fresh material coating over these upper surfaces. After this material settles, a fresh layer of building material will have formed over the upper surfaces, to redefine a new working surface of the material at level L2 which is the upper surface of this fresh layer. Typically, this lowering is accomplished by down-dipping the partially formed part below the working surface. Other relative movement means are possible, including means for adding to or extracting material from the container, or means for moving the container itself relative to the partially-formed part. In the subsequent discussion, the time to form a fresh layer of material over a previously-transformed layer will be referred to as the "recoating time," and the process of

forming a first layer over a previously-transformed layer will be referred to as the "recoating process" or "recoating" step. At this point, a layer of untransformed material has been formed at the appropriate thickness in anticipation of forming layer 805. This layer is then transformed upon selective exposure of material at the redefined working surface to the synergistic stimulation. As shown, this layer has a lower surface which is adhered to the upper surfaces of fill layer 807a and structural layer 806, in the manner described previously, and an end 805' which abuts against envelope 810.

A significant advantage of this example is that layers 806, 807a, 807b and 807c can all be formed while the working surface is located at level L1, so that there is no additional recoating time required over what would be required to form the structural layers.

On the other hand, the method may have the slight disadvantage that the thickness of the fill layers may be more difficult to control since the required exposure to form each fill layer after the first one (layer 807a in the figure) depends on the already-applied exposure used to form previous layers. Another disadvantage may be that the exposure used to form the first fill layer 807a may be so low that it requires a speed of scanning of the beam that may exceed the speed and control limitations of the scanning. Therefore, to accomplish this fast scanning, a faster and more appropriate set of scanning mirrors must be used, or the intensity of the synergistic stimulation must be reduced in some manner. This in turn makes the process more difficult and costly. Another disadvantage may be that the layers 807a, 807b and 807c may have low structural strength. These layers will gain more strength after they have been adhered, from above, to the next structural layer 805 that will be formed. However, before this can happen, these layers may be subjected to forces which result from coating the upper surface of layer 806 with fresh material in anticipation of forming layer 805.

These fill layers may be lacking in sufficient cohesiveness or rigidity to withstand these forces before adherence to layer 805. It is noted that the exposure given to form a layer may vary from region to region depending on whether the regions are used for adhesion or for forming a down-facing region. For example, the end of 805 near 805" forms a down-facing region and will be given an appropriate exposure to form the down-facing feature at the right position, whereas the remaining portions of layer 805 may be given greater exposure to ensure adhesion.

Turning now to Figure 56b, a second example is shown which is similar to that illustrated in Figure 56a, except that fill layers 807a, 807b and 807c are formed edgewise, instead of lengthwise. Layer 807a in the figure, has a surface which is adhered to the end 806' of structural layer 806. The other fill layers have surfaces which are adhered to adjacent fill layers.

Each of the fill layers has a different depth. The non-uniform depths of the fill layers can be achieved by varying the exposure used to form each layer. Again, considering a material obeying Beer's Law and applying the principles discussed in U.S. Patent Application 07/339,246 if the exposure required to form layer 807c is E_1, and a fill layer penetrates 4 mils beyond layer 805, then for the photopolymer in the previously discussed example, the required exposure required to form layer 807b will be twice E_1. Of course, if the incremental increase in cure depth were 8 mils, the required exposure would be four times E_1. Note that the order of forming the fill layers, which is illustrated, is 807a, 807b and followed by 807c. This is to ensure that each successive layer has a solid anchoring point to attach to as it is formed, thereby ensuring that the fill layers do not shift out of their appropriate position as they are formed.

After the formation of the fill layers, the first ends of the fill layers, and the upper surface of layer

806 are coated with a layer of fresh material. This fresh material is then exposed to form layer 805.

The benefits of this example are similar to those discussed earlier with respect to Figure 56a, and will not be repeated. An additional advantage of this example, however, is that layers 807a, 807b and 807c are formed edgewise instead of lengthwise as in Figure 56a, enabling layers 807b and 807c to be formed without requiring exposure thorough previously-formed layer 807a.

A third example, and most preferred embodiment of the subject invention for the filling of discontinuities at down-facing regions, is shown in Figure 56d, which compared to the first three examples has greater structural strength. This is because, as will be seen, layer 805 is formed before the forming of the fill layers, so that the top-most fill layer can be adhered to it before any additional recoating must occur. First, layer 806 is formed directly at the working surface which is at level L1, and then the upper surface of this layer is lowered relative to the working surface to define a new working surface located at level L2, at which point layer 805 is formed. Next, while the level of the working surface remains at level L2, which is tangent with the upper surface of layer 805, fill layers 807a, 807b and 807c are formed by exposure through layer 805. These fill layers are formed edgewise, as shown, out of material below the lower surface of layer 805 (which is below the working surface) by varying the exposure of the synergistic stimulation sufficiently so that it penetrates through layer 805 and into the material below the lower surface of layer 805 (at the extension region 805") to form the fill layers. The amount of exposure required for each layer can be determined based on the cure depth and exposure required for the particular fill layer under consideration and the amount of exposure already applied to form layer 805.

As mentioned previously, an important aspect of this example is the formation of structural layer 805 before fill layers 807a, 807b and 807c. This results in these fill layers being adhered to layer 805 as they are formed. Consequently, these layers will have greater structural strength and greater support as the rest of the part is built, compared with the previous examples. This is especially important as the fill layers may be subjected to substantial forces throughout the recoating process.

Note that in this example, the order of the formation of the fill layers is to be 807a, 807b and 807c. This is to provide additional structural strength to the fill layers in that a surface of layer 807a can be first adhered to the edge 806" of layer 806 before the other fill layers are adhered to it. If the order of formation were reversed, the ends of layers 807c and 807b would only be adhered to the extension region 805" of layer 805 before the formation of layer 807a. However, since the structural strength of layers 807b and 807c may still be sufficient to withstand the bending forces, the subject invention is intended to encompass the formation of the fill layers in any order.

An alternative to this embodiment is shown in Figure 56d. Figure 56d depicts a building technique similar to that of Figure 56c in that the fill layers are formed after the formation of layer 805, by exposure through layer 805, except that the fill layers are formed lengthwise instead of edgewise. The result is that fill layer 807a is cured by exposure through already-formed layer 805, layer 807b is cured by exposure through layers 805 and 807a, and layer 807c is cured by exposure through layers 805, 807a and 807b.

The filling in of surface discontinuities of up-facing features will now be described.

Examples of filling in surface discontinuities of up-facing features are illustrated in Figures 57a-57e, in which compared to Figures 56a-56e, like elements are

referred to with like numerals. As with the down-facing embodiments, Figures 57d and 57e depict the most preferred embodiments. One difference, however, is that consistent with the definition of an up-facing feature, larger structural layer 805 is placed below adjacent shorter structural layer 806, instead of above it.

Each layer in Figures 57a-57e has a corresponding circled numeral, which indicate the sequence in which the layers are built.

The first example for filling in discontinuities at up-facing features is illustrated in Figure 57a. As shown, before the formation of the fill layers, structural layer 805 is first formed while the working surface is at level L1. Structural layer 806 is then formed which has a lower surface adhered to an upper surface of layer 805. Layer 806 is formed after the working surface has been redefined to be at level L2. In addition, the exposure used to form layer 806 need not be precisely determined, since the cure depth of layer 806 can be extended into layer 805 without sacrificing the accuracy of the part. Edge 805' of layer 805 also extends beyond edge 806' of layer 806 by extension region 805". The sequence of building the fill layers is as follows: first, the partially formed part is raised relative to the working surface such that a thinner layer of untransformed material is recoated over the extension region. At this point, the upper surface of the untransformed layer defines a new working surface at level L3.

Next layer 807a is formed, and adhered to extension segment 805".

Note that the formation of a coating of untransformed material over the extension region in anticipation of forming layer 807a may take a significant amount of time because of the viscosity of the material involved.

The partially formed part comprising layers 805, 806 and 807a is then lowered relative to the working surface at L3 so that a layer of untransformed material will form

over the upper surface of layer 807a' to define a new working surface which is one fill layer thickness above the upper surface of layer 807a' at level L4.

Note that any bending forces exerted on the layers by the recoating process, will not appreciably deform layer 807a, since its lower surface will be adhered to the extension region of structural layer 805 throughout this process, and should be able to withstand those forces. In addition, layer 807a can be made even stronger by overexposing it, since any increase in cure depth resulting from this exposure will mainly penetrate into the already-formed layer 805 and not harm part resolution. This additional exposure will therefore enhance adhesion between layers 807a' and 805, and will also further harden the material within the nominal layer thickness of layer 807a.

Turning back to the formation of the fill layers in Figure 57a, after the formation of layer 807a, as already stated, the partially-formed part is lowered relative to the new working surface to define a newer working surface at level L4. At this point, layer 807b is then formed.

Finally, after the formation of layer 807b, the partially-formed part is lowered again relative to the working surface, and a layer of untransformed material is recoated over layer 807b to form a new layer of untransformed material having an upper surface which defines a newer working surface at level L5. At this point, layer 807c is formed.

As may be observed from Figure 806b, the plurality of meniscuses which form at the ends of layers 807a, 807b and 807c, identified as 807a', 807b' and 807c', may have the beneficial effect of smoothing the surface discontinuity more than would otherwise be the case, so that the surface formed by the meniscuses more closely matches the envelope of the corresponding object representation 810, than does the surface formed by the ends of the fill layers as shown in Figure 57a. Therefore, it may be advantageous to form

layers 807a, 807b and 807c and/or meniscus regions 807a', 807b' and 807c' while the corresponding working surface is in transition.

Figure 57b depicts an embodiment similar to that of Figure 57a but where the viscosity and/or surface tension of the building material is used to advantage to form slanting end caps at the ends of the fill and structural layers in order to give a smoother surface finish than that obtained with the fill layers alone. This embodiment is practiced in several ways.

A first method of practice is to form layer 805 with the material surface at level L1, followed by the formation of layer 806 with the material surface at level L2. Next, fill layer 807a is formed while the material surface is at L3. This is followed by the relative movement of the material surface to level L3'. Before the material which is adjacent to layer 807a completely recedes to level L3', this material is transformed to form meniscus region 807a'. This meniscus region gives the outer edge of layer 807a a tapered appearance and thereby reduces the discontinuity further. Next, the level is adjusted to level L4 and fill layer 807b is formed followed by an additional adjustment to level L4' and the formation of meniscus region 807b'. Similarly, fill layer 807c and meniscus region 807c' are formed with the material level adjusted to levels L5 and L5', respectively. Finally, the level is adjusted upward to at least level L2 wherein the region above 807c will be coated with material. Then, the level is readjusted to level L6' and meniscus region 807d' is transformed.

A second method of practice involves the formation of fill layers 807a simultaneously with meniscus region 807a'. Similarly, fill layer 807b and meniscus region 807b' are formed simultaneously. Also, fill layer 807c and meniscus region 807c' are formed simultaneously, followed by the formation of meniscus region 807d'. These fill layers and meniscus regions are formed with the

material surface level at positions L3', L4', L5', and L6', respectively. Initially, layer 805 is formed with the material level at L1, followed by the formation of layer 806 while the material level is at L2. Next, the material level is relatively decreased to level L3' where prior to complete material recession from above extension region 805", fill layer 807a and meniscus region 807a' are transformed by exposing the receding material surface to synergistic stimulation. This exposure and transformation forms a solidified fill layer and end cap that approximates those depicted in Figure 57b except that here, the fill layer and meniscus region together form a larger combined meniscus region. Next, the material level is raised to at least level L5' and the material is allowed to coat over region 807a and 807a'. After this coating process, the level is decreased to level L4' and fill layer 807b and region 807b' are exposed and transformed forming a second combined meniscus region. Sufficient exposure is applied to ensure adhesion between 807a and 807b and 807a and 807b'. In a similar manner, the material level is raised to at least level L6' where the material is allowed to coat over 807b and 807b' after which the level is reduced to L5'. At this point, 807c and 807c' will be transformed. Finally, 807c and 807c' will be recoated with fresh material by bringing the level to at least L2', thereby allowing recoating to occur. Next, the level is reduced to level L6' and region 807d' is transformed.

The examples of Figure 57a and 57b, while very useful for some parts, may not be completely acceptable for other part geometries. This is because these geometries may require excessively long recoating times to obtain appropriate working surfaces at levels L3, L4, and L5, before formation of each fill layer. In addition, part geometries having trapped volumes will be problematic since the trapped volumes will prevent excess material

from flowing off of a surface after the formation of layer 806.

Turning to Figure 57c, another example of filling an up-facing feature will now be described. In this example, a layer of material is first formed to define a working surface at level L1, and then layer 805 is formed. A layer of material will be recoated over the upper surface of layer 805 having an upper surface defining a new working surface at level L2. Here, a doctor blade can be effectively used to enhance the recoating rate since layer 806 is not yet formed. Layer 806 is then formed and adhered to layer 805. Next, extension region 805" is coated with a layer of material whose upper surface defines a newer working surface at level L3. Since the thickness of this layer is substantially larger than the thickness of the fill layer thicknesses as defined in the example of Figure 57b, the time to recoat will be faster compared with the time required in the previous examples. Edgewise layer 807a is then formed. As with the example described in Figure 57b, layer 807a can be transformed prior to complete surface level relaxation to level L3 thereby forming a transformed meniscus region above fill layer 807a. Next, a layer of material is formed over the remainder of the extension region which forms a newest working surface at level L4. Then, layer 807b is formed as well as possibly a meniscus region above 807b. Finally, a newest working surface is created at level L5. Layer 807c is then formed. If this embodiment were to be combined with meniscus transformation, discussed previously, the surface level would be decreased to L1, and then prior to complete leveling, the meniscus next to 807c would be transformed.

Note that this example illustrates forming the fill layers in the order 807a, 807b and 807c. This order was chosen for its structural strength compared to other orders, as well as its benefits for faster recoating. However, other orders such as 807c, 807b and 807a may

provide the necessary structural strength, and not be too slow in terms of recoating times, and are therefore meant to be encompassed.

This example improves on the examples of Figures 57a and 57b, since the edgewise formation of layers may significantly decrease the recoating time, although it may not completely solve the problems of these earlier examples.

A next, and most preferred example for filling discontinuities at up-facing features, is illustrated in Figure 57d. This example is most preferred, since, unlike the previous examples, the required coatings can be obtained regardless of part geometry, and additionally, a doctor blade or the like can be used to speed up recoating for the fill layers since this example ensures that the upper surface of a previously solidified layer will never block movement of the doctor blade. In the example of Figure 57d, layer 805 is formed as described earlier while the working surface is at level L1, and then edgewise layers 807a, 807b and 807c are successively formed in the order indicated, while the partially formed part is increasingly lowered, and the working surface is progressively redefined at levels L2, L3, and L4, respectively. Lastly, after the partially formed part has been lowered again to define the working surface at level L5, layer 806 is formed.

A next example, and another most preferred method of filling up-facing discontinuities is depicted in Figure 57e. In this example, layer 805 is formed while the working surface is located at position L1. The uppermost surface of layer 805 is then lowered relative to the working surface, such that a new working surface is formed at level L2. Fill layer 807a is then formed situated lengthwise as shown. The partially formed part is then lowered relative to the working surface so that the working surface is repositioned relative to the part at level L3. Fill layer 807b is then formed. The partially

formed part is then lowered again relative to the new working surface, so that the level of the new working surface is repositioned at L4. At this point, layer 807c is formed. Finally, the partially formed part is lowered once again relative to the working surface to reposition the working surface to level L5. At this point, layer 806 is formed.

In the example of Figure 57d, the edgewise formation of the fill layers may allow somewhat faster recoating of the fill layers. On the other hand, the example of Figure 806e may offer somewhat stronger fill layers since they are horizontally longer.

It is noted that in the previous figures, only three (3) fill layers per structural layer were illustrated for each example. In a given situation, however, the number of fill layers per structural layer can be any number from one upward. Therefore, the examples are not intended to be limiting regarding the number of fill layers.

The particular examples of Figures 56a-56e show fill layers having a thickness which is about 1/4 the thickness of the structural layers, i.e., if the structural layer thickness were 20 mils then the fill layer thickness would be 5 mils. The net result of adding these fill layers is an object having 20 mil structural layers built with a surface discontinuity which is characteristic of an object built with 5 mil structural layers. If fill layers were to be one-half the structural layer thicknesses, then there would be one fill layer for each structural layer. For a 20 mil structural layer thickness the use of such fill layers would result in a surface resolution substantially equivalent to that of a part built with 10 mil layers. On the other hand, if the structural layer thickness were 5 mils then a surface resolution characteristic of a part built with 2.5 mil layers would result. These concepts are depicted in Figures 58a and 58b. Figure 58a depicts a side view of two structural layers 805 and 806 and three fill layers 807a, 807b and 807c that

are used to reduce the discontinuity between the structural layers. Figure 807a depicts a ratio of fill layer thickness to structural layer thickness of 1/4. Figure 58b depicts a side view of two structural layers 805 and 806 and seven fill layers 807a, 807b, 807c, 807d, 807e, 807f and 807g. Figure 58b depicts a ratio of fill layer thickness to structural layer thickness of 1/8. Comparing Figures 58a and 58b, it can be seen for a given structural layer thickness, a smaller ratio leads to higher surface resolution, i.e., a surface which deviates less from the corresponding object representation.

Since the angle between the surface normal of the object representation and the vertical will vary from region to region within a given cross-section and from cross-section to cross-section as an object is formed, the length and width of the fill layers required at each region will also vary.

Also, the lengthwise fill layers depicted in the examples are shown having uniform thicknesses, and the edgewise layers are shown as having a uniform width. In addition, the extent to which a fill layer extends beyond an adjacent, lower fill layer ("overhang length") is also shown to be constant. Under some circumstances, it will be advantageous to deviate from those uniform sizes. These circumstances include situations where the envelope does not linearly connect the two structural layers which bound the surface discontinuity at issue, or situations where non-uniform spacing may enhance buildability with only a slight sacrifice in part accuracy. Such situations are depicted in Figures 59a, 59b and 59c, which show the benefits of a non-uniform layer thickness and overhang length. Figure 59a depicts a situation where the overhang length for the fill layers is maintained constant, but the thickness of the fill layers 807a, 807b and 807c is varied in order to compensate for the non-linearity of the envelope 810. Figure 59b depicts the situation where the thickness of the fill layers 807a, 807b and 807c is

maintained constant, and the non-linearity of the envelope 810 is compensated for by using non-uniform overhang lengths for the fill layers. Figure 59c depicts a situation where two structural layers 805 and 806 are connected linearly by object representation envelope 810, but where the fill layers 807a, 807b and 807c still are built with either non-uniform thicknesses or overhang lengths.

Regarding this later example, it can be seen from Figure 59c that the extent of the discontinuity bounded by structural layers 805 and 806, and by object representation envelope 810, is greatly reduced by inclusion of the fill layers even though the fill layers do not uniformly and fully fill the discontinuity. When the building material being used cannot form adequately cohesive unsupported fill layers which are as thin or as long as required to completely fill the discontinuity, the thickness of the fill layers may have to be increased, or the length of the lengthwise fill layers may have to be decreased, in order to form fill layers which have sufficient structural strength to withstand the bending forces exerted on them before the formation of layer 805.

Turning now to in Figures 60a, 60b and 60c, these figures depict two structural layers 820 and 822, which, compared to the earlier figures, are shown intersecting the envelope of the object representation at more than one region. Figure 60a, for example, depicts two regions 824 and 826 of the envelope of the object representation which intersect the layers. Therefore, these structural layers, in general, define more than one surface discontinuity. In Figure 60a, for example, portion 824 of the envelope bounds discontinuity 828; which is located at an up-facing feature of the object, while portion 826 of the envelope bounds discontinuity 830 which is located at a down-facing feature of the object. It should be recognized that, according to the teachings of the instant invention, both of these discontinuities could be filled

in by fill layers. Figure 60b depicts the discontinuity 828 being filled by lengthwise fill layers 807a, 807b and 807c. It also depicts discontinuity 830 being filled by lengthwise fill layers 807a, 807b and 807c. Figure 60c depicts the object of Figure 60b as seen in two dimensions, whereas the illustrations of Figures 60a and 60b provide a three-dimensional perspective.

The examples are described in terms of building up layers one on top of the other so that the object builds up in the vertical dimension, but other orientations of layer to layer build-up are possible such as forming the part where successive layers are underneath previous layers or where successive layers are placed beside previous layers. Additionally, it is appreciated that one may desire to reduce surface discontinuities for aesthetic appeal without necessarily increasing accuracy of the produced part. For example, it is appreciated that one may apply the techniques of the present invention to an over-sized building style, whereby surface discontinuities are reduced compared to a desired object envelope which is larger than the envelope of the object representation, even though this will reduce the overall accuracy of the part compared to the envelope of the object representation. Therefore, the examples shown here are not meant to be limiting, and the subject invention is intended to encompass smoothing out an object relative to a desired object envelope which may be different from an envelope of an object representation.

The discussion up to this point has emphasized various methods of forming fill layers in sloped up-facing or down-facing regions without regard to transition regions. A viable method of discontinuity reduction must also consider problems associated with and methods for dealing with various transition regions. Transition regions are those regions where an up or down-facing slanted region meets a vertical, a flat, or an oppositely slanted region. Several such transition regions are

depicted in Figures 61a-61j. Figure 61a depicts a transition from a down-facing slanted feature to a vertical feature. Figure 61b depicts the opposite transition: a transition from a vertical feature to a down-facing slanted feature. Figures 61c and 61d depict another pair of transitions: transitions between slanted down-facing features to horizontal features. Figures 61e-61h depict a corresponding set of transitions but pertaining to slanted up-facing features and Figures 61i and 61j depict a pair of complementary transitions between up-facing and down-facing slanting features.

Figure 62a depicts the transition region of Figure 61a as reproduced using a traditional undersized building technique. This figure depicts the formation of the region by four structural layers 902, 904, 906 and 908. Also depicted is line 910 that represents the envelope of the computer generated object.

Figure 62b depicts the same transition region and structural layers as Figure 62a, except that Figure 62b additionally depicts down-facing fill layers 912, 914 and 916 that occur within a continuing down-facing slanted region. This figure additionally depicts fill layers 918, 920 and 922, which are directly below the transition region. In Figure 62b, it can be seen that these fill layers can be formed with the methods of Figure 56c or 56d since it is guaranteed that there will be a structural layer over the region of these fill layers that can be exposed through.

Figure 62c depicts the same transition region as did Figures 62a and 62b but this time the object, and therefore transition region, is formed using an oversized building style. Like elements of Figure 62c and Figure 62a are labeled with like reference numerals. Figure 62d represents one selection of a pattern of fill layers to create a slightly oversized object. These fill layers are labeled as 924, 926, 928, 930, 932, 934, 936 and 938. Lines 940 and 942 represent the outline of the

oversized object as it would be formed without the fill layers. As with Figure 62b, it can be seen that fill layers 932, 934, 936 and 938, which are associated with the lower transition layer 904, can be formed by one of the preferred methods since the structural portion of the upper transition layer 906 extends out to the end of the shallowest fill layer 938. Therefore, for this transition region, it can be concluded that the preferred methods of forming fill layers can be used successfully for either oversized or undersized object formation.

Figures 63a, 63b, 63c and 63d depict identical structures as that of Figures 62a, 62b, 62c and 62d except they are instead based on the transition region of Figure 61b. Compared to earlier figures, here, like elements are labeled with like numerals. As can be seen, the fill layers of this transition region can also be built utilizing the preferred methods of Figures 56c or 56d. Figure 63c depicts fill layers 950, 952 and 954 adjacent to upper transition structural layer 906. It also depicts fill layers 956, 958 and 960. Figure 63d depicts fill layers 962, 964, 966 and 968 adjacent to upper transition structural layer 906. It also depicts fill layers 970, 972, 974 and 976. Lines 978 and 980 represent the outline of the oversized object as it would be formed without the fill layers.

Figures 64a, 64b, 64c and 64d depict identical elements as those of their respective counterparts in Figures 62 and 63, and as such are similarly labeled. Examination of Figures 64b and 64d reveal that the fill layers associated with lower transition layer 904 cannot be handled by previously-discussed preferred methods since an appropriate upper fill layer 906 does not exist. Therefore, it is concluded that the fill layers 918, 920 and 922 of Figure 64b or the fill layers 932, 934, 936 and 938 of Figure 64d must be formed by one of the other methods described in Figures 56a or 56b or the like. Alternatively, one may choose not to form these fill

layers at all. In either case, in terms of a generalized implementation, it becomes necessary to utilize multiple layer information to determine how to form the fill layers associated with a given structural layer (at least if one wishes to use the preferred methods of formation as often as possible). Part building experience indicates that transition regions of the Figure 61c type are not encountered often and, therefore can be handled by other alternative methods. One alternative method involves the inspection of the original three dimensional object data to see if such regions exist. If not, the object can be built according to a preferred method. If they do exist, the portion of space containing the region can be given an attribute which indicates to the computer not to form fill layers for that portion.

Figures 65a, 65b, 65c and 65d are similar to their corresponding counterparts in Figures 62, 63 and 64 except that these figures are based on the transition region of Figure 61d. It can be seen that the layer above the upper transition layer extends at least as far as the thinnest fill layer and therefore the fill layers can be formed according to one of the preferred methods of formation.

Figures 66 to 69 are counterparts to Figures 62 to 65 but for up-facing slanted surfaces instead of for down-facing slanted surfaces. Figure 66 depicts the transition region of Figure 61e. Figure 67 depicts the transition region of Figure 61f. Figure 68 depicts the transition region of Figure 61g, and Figure 69 depicts the transition of region of Figure 61h. For up-facing slanted features, the utilization of the preferred formation methods requires that the lower transition layer extend completely under the thinnest of the fill layers associated with the upper transition structural layer. The elements of Figures 76 to 69 are labeled with like numerals to their counterparts in Figures 62 to 65. Examination of these Figures indicate that the transition regions of Figures 66, 67 and 69 can be produced by the preferred

methods (those of Figure 57d or 57e). However, examination of Figure 68 indicates that utilization of a preferred method might result in some difficulties since there is not a lower transition layer to support the fill layers. Therefore, utilization of a preferred method in this case would require the use of support structures (like the web supports described in U.S. Patent Number 4,999,143). Alternatively, one of the other formation methods of Figures 57a, 57b or 57c can be used or a decision can be made not to produce fill layers in association with the upper structural layer of this particular transition region.

Figures 70a, 70b, 70c and 70d depict the transition zone of Figure 61i. As can be seen from this figure, the lower transition layer 904 comprises down-facing fill layers and upper transition layer 906 comprises up-facing fill layers, wherein the upper fill layers are above the down-facing fill layers. Therefore, the up-facing fill layers do not have a full structural layer below them to give them support. This problem can be handled as described above for Figure 68. However, it is noted that the down-facing fill layers cannot be exposed through a complete structural layer to give them support. This problem can be handled in the same way as described for that of Figure 64.

Figures 71a, 71b, 71c and 71d depict the transition region of Figure 61j. As can be seen from the figures, the fill layers of this transition region can be appropriately formed by our preferred methods.

In summary, 7 of the 10 transition regions can be appropriately handled by the preferred formation methods whereas the other three transition regions require other methods for proper formation. These three special regions can be formed following the above outlined steps or, alternatively, they can be handled by appropriate utilization of the building methods described in Section Z.

Keeping the above considerations in mind, methods of implementing the above-described preferred methods will now be described based on the assumptions that the three previously-discussed transition regions do not exist or that the portions of space that include them are attributed in such a way that the fill layers will not be formed, or if formed, will be associated with appropriate structural layers.

Implementation

A first method of implementation is based on forming a slightly oversized object as depicted in the "d" figures of Figures 62 through 71. The formation of fill layers is based on the methods described in Figures 56d and 56d or alternatively Figures 56e and 56e. This implementation is based on the SLICE program described in detail in publication WO 89/10256.

A preferred method of forming objects described in this application is directed to forming oversized objects. This publication WO 89/10256 identifies the primary regions that would profit from the utilization of fill layers as near-flat up-facing regions and near-flat down-facing regions. For a region (triangle) to be considered near-flat, the angle between the region (triangle) normal vector and the vertical axis must be less than a user specified value for an option known as the MSA. If the MSA value is set close to 90 degrees, then substantially all the non-flat and non-vertical triangles will be considered near-flat.

Down-facing near-flat triangles form areas that are substantially non-overlapping with other areas produced for a given layer. There is the possibility that there may be some overlap with flat up-facing and near-flat up-facing regions. If overlap exists for a given object, then for accurate reproduction of the object, the overlap must be removed. Since the down-facing near-flat triangles substantially dictate the regions for fill

layers and they form substantially independent areas, then for the present program to be successfully modified to produce fill layers, the processing that is done to these particular triangles must be modified. This modification consists of slicing the near-flat down-facing triangles at slicing intervals appropriate to the thickness of the fill layers.

Figures 72 to 75 depict examples of implementations of the subject invention. In these examples, the fill layers have thicknesses which are 1/4 of that of the structural layer thickness.

Figure 72 depicts a two-dimensional side view of slicing planes 1200 and 1202 and of the only visible edge of triangle 1204. The region to the left of triangle 1204 comprises a portion of the object while the region to the right is empty space. The upward direction is indicated by arrow 1206. Thus, 1204 represents a down-facing near-flat triangle. In the normal processing of triangle 1204, the region depicted between planes 1200 and 1202 and bounded by line 1208 and line 1210 would be produced and labeled as a near-flat down-facing region. It would be associated with a cross-section corresponding to slice plane 1200 but which specifies material to be transformed that corresponds to the region between planes 1200 and 1202. Instead of creating this singular rectangular box to be cured, by use of additional slice planes and additional processing, smaller rectangular regions 1212, 1214, 1216 and 1218 can be separately produced and labeled to form fill layers of different thickness. Area 1226 of fill layer 821 is formed by slicing triangle 1204 at slice plane 1200 and 1220 and projecting the area (a line in this two dimensional view) to the appropriate cross-section. In terms of the preferred methods of forming fill layers discussed previously, this area 1226 would be associated with the cross-section 1201 (which the output of SLICE would label as 1202). This area is one structural layer higher than the box between 1202, 1200,

1208 and 1210 (which is associated with 1200). This area 1226 would be labeled as requiring a cure depth of 1 full structural layer thickness to form fill layer 1212, but since it will be exposed through an already existing layer, its actual thickness will be two layer thicknesses. An appropriate exposure level will be specified by the user or determined by the system. Area 1228 of fill layer 1214 is obtained by slicing the triangle at slicing planes 1220 and 1222 and projecting the net area to the same cross-section that 1226 was associated with. However, in this case, the cure depth associated with this area will be 3/4 of a layer thickness. Actually, the thickness will be 1 and 3/4 layer thicknesses because of the method of exposing though a previously cured layer. Area 1230 of fill layer 1216 will be obtained by slicing at planes 1222 and 1224 and projecting the portion of the triangle between the planes to the same plane that 1226 and 1228 were associated with, along with the labeling and specification for a cure depth of 1/2 (or 1 and 1/2) layer thicknesses. Area 1232 of fill layer 1218 will be formed in an analogous manner by use of slicing plane 1224 and 1202. Its corresponding cure depth will be 1/4 (or 1 and 1/4) of a layer thickness.

The above description called for the formation of fill layers in an edgewise manner and it therefore corresponds to the method of Figure 56c. A similar implementation based on the method of Figure 56d could be developed based on similar slice planes but where the comparisons between planes would be modified and the cure depths modified. This is outlined in Figure 73. Fill layer 1240 is obtained by slicing at planes 1200 and 1202 and projecting the intervening area of triangle 1204 between the planes to the appropriate cross-section, and then labeling and specifying a cure depth of 1/4 layer (1 and 1/4 layer). Fill layer 1238 is obtained by slicing triangle 1204 at planes 1224 and 1200 and projecting the intervening area of 1204 between 1224 and 1200 to the

appropriate layer (same as 1240), labeling and specifying a cure depth of 1/4 of a layer thickness below fill layer 1240 (1 and 1/2 layers). Similarly, fill layer 1236 is obtained from slicing planes 1222 and 1200 and its cure depth is 1/4 of a layer thickness below fill layer 1238 (1 and 3/4 layers). Finally, fill layer 1234 is obtained from slice planes 1220 and 1200 and its cure depth is 1/4 of a layer thickness below fill layer 1236 (2 layers).

According to this same SLICE program, the near-flat up-facing triangle regions form areas that overlap other regions. The most important of these other regions are the layer boundary areas. The down-facing flat and near-flat regions may also be overlapped; however, this condition belongs to the cases that have been excluded (transition regions of Figure 61g and 61j). In any case, the flat down-facing region can be compensated for by appropriate use of supports. Since layer boundary areas and flat down-facing areas are considered to be worthy of at least a full structural layer thickness cure depth, these areas must be removed from the near-flat up-facing areas because it is desirable to cure the near-flat up-facing areas in a staged manner where effective cure thickness is less than or approximately equal to 1 layer thickness. Therefore, the first step in the process of forming the up-facing fill areas is to subtract the up-facing near-flat regions from the layer boundary (and flat down-facing boundary and near-flat down boundary) regions so that separate and distinct regions are formed. Methods based on a more direct layer comparison version of SLICE are described in Section 1. After the separation of regions has occurred, the up-facing near-flat triangles substantially dictate the regions for fill layers and they form substantially independent areas. From this point, for the present SLICE program to be modified to produce fill layers, the processing that is done to these particular triangles must be modified. This modification consists of slicing the near-flat up-facing triangles at

slicing intervals appropriate to the thickness of the fill layers.

Figure 74 depicts an up-facing analogy to Figure 72, and as such, like elements are labeled with like numerals. Figure 74 depicts a two-dimensional side view of slicing planes 1200 and 1202 and of the only visible edge of triangle 1204. The region to the right of triangle 1204 comprises a portion of the object while the region to the left is empty space. The upward direction is indicated by arrow 1206. Thus, 1204 represents an up-facing near-flat triangle. In the normal processing of triangle 1204, the region depicted between planes 1200 and 1202 and bounded by line 1208 and line 1210 would be produced and labeled as a near-flat up-facing region. It would be associated with a cross-section corresponding to slice plane 1200 but which specifies material to be transformed that corresponds to the region between planes 1200 and 1202. Instead of creating this singular rectangular box to be cured, by use of additional slice planes and additional processing, smaller rectangular regions 1212, 1214, 1216 and 1218 can be separately produced and labeled to form fill layers of different thicknesses. Area 1226 of fill layer 1212 is formed by slicing triangle 1204 at slice planes 1202 and 1224 and projecting the area (a line in this two-dimensional view) to the appropriate cross-section. In terms of the preferred methods and the figure as illustrated, this area 1226 would be associated with the cross-section 1202 (actually 1200 since the SLICE program in essence shifts everything downward by one layer thickness). This region 1226 would be labeled as requiring a cure depth of 1 full structural layer thickness (plus any necessary overcure) to form fill layer 1212. Area 1228 of fill layer 1214 will be obtained by slicing the triangle at slicing planes 1224 and 1222 and associating the intervening area with the cross-section associated with slicing plane 1224 (or 1 structural layer below that in terms of the 1 layer down shift). In this

case, the cure depth associated with this area will be 3/4 of a layer thickness plus any necessary overcure. Area 1230 of fill layer 1216 will be obtained by slicing at planes 1222 and 1220 and associating the intervening area to the cross-section associated with slice plane 1222 along with the labeling and specification for a cure depth of 1/2 a layer thickness (plus overcure). Area 1232 of fill layer 1218 will be formed in an analogous manner by use of slicing planes 1220 and 1200. Its corresponding cure depth will be 1/4 of a layer thickness (plus overcure). This above description called for the formation of fill layer in an edgewise manner and therefore corresponds to the method of Figure 57d.

A similar implementation of the method of Figure 57e is possible which is based on similar slice planes where the comparisons between planes would be modified and the cure depths modified. This is outlined in Figure 75. Fill layer 1240 is obtained by slicing at planes 1200 and 1202, associating the net area with the cross-section corresponding to slice plane 1220, and then labeling and specifying a cure depth of 1/4 layer (plus any necessary overcure). Fill layer 1238 is obtained by slicing triangle 1204 at planes 1220 and 1202, projecting the area of 1204 that is between 1220 and 1202 to the cross-section associated with 1222, and then labeling and specifying a cure depth of 1/4 of a layer (plus any necessary overcure). Similarly, fill layer 1236 is obtained from slicing planes 1222 and 1202. It is associated with slicing plane 1224 and its cure depth is 1/4 of a layer thickness (plus any overcure). Similarly, fill layer 1234 is obtained from slice planes 1224 and 1202. It is associated with plane 1202 and its cure depth is 1/4 of a layer thickness (plus any overcure).

A second method of implementation is based on forming a slightly undersized object. This implementation can be based on the SLICE program of the above discussion or on the SLICE program described in Section 1. This imple-

mentation is substantially the same as the previously-described oversized implementation except in this implementation, the cure depth associated with each fill layer of Figure 72 is decreased by 1/4 of a layer thickness. The fill layers of Figure 74 are decreased in thickness by 1/4 of a layer thickness, but furthermore, the planes with which they are associated are shifted downward. Fill layer 1226 would be associated with plane 1224, while fill layers 1228, 1230 and 1232 would be respectively associated with planes 1222, 1220 and 1200. This, in turn, effectively means that fill layer 1232 would disappear. The slicing planes used to obtain the fill layers of Figure 73 would be

Fill Layer	Planes
1240	1200 and 1224
1238	1200 and 1222
1236	1200 and 1220
1234	1200 and 1200 = No Generation.

Similarly, the slicing planes and associated cross-sections used to obtain the fill layers of Figure 75 would be

Fill Layer	Planes	Cross-section
1240	1202 and 1220	1220
1238	1202 and 1222	1222
1236	1202 and 1224	1224
1234	1202 and 1202 = No Generation.	

The generalization of the above implementations to different numbers of fill layers will be apparent to one of ordinary skill in the art.

Various other implementations are possible and will be apparent to one of ordinary skill in the art by following the teachings of this disclosure. For example, implementations that simply reduce discontinuities as opposed to simultaneously achieving higher levels of reproduction accuracy are conceivable and may have application in those market segments that are primarily

concerned with visual appeal as opposed to accurate representation.

Because of the computational simplicity of the layer comparison SLICE (Section 1) in terms of determining intersecting regions and separating them, the above oversized and undersized implementations may be easily made available through appropriate modifications to this version of SLICE.

A problematic aspect with the first and second implementation embodiments, however, is, as discussed in WO 89/10256 that triangle vertices of the object representation are rounded to the slicing planes corresponding to the structural layers before formation of the boundaries. As a result, even though a vertex may be closer to a slicing plane corresponding to a fill layer, it will still be rounded to the closest structural layer slice plane. This step is performed for computational efficiency, but it may result in a loss of accuracy. Therefore, a further modification of SLICE, whereby triangle vertices are rounded to the nearest slicing plane, even those corresponding to the fill layers, could be made in order to obtain even higher part accuracy at the expense of some loss of computational simplicity.

A third method of implementation involves modifying SLICE in this fashion. Specially, all triangle vertices are rounded to the closest slicing plane, whether it be a structural layer slicing plane or a fill layer slicing plane. The elements necessary for this third method of implementation are described in Section 2. In addition to the benefit of more accurate part reproduction, this third method also involves modifying SLICE to build layers to a thickness, whenever possible, which may be greater than the desired fill layer thickness, but which is necessary to build layers of acceptable thickness and rigidity.

As described in WO 89/10256 different cure depths generally result in different cure widths. Therefore, in practicing the present invention, as described in the

previous embodiments, it may be desirable to utilize an appropriate cure width compensation algorithm for each region to adjust the boundaries of regions depending on the particular cure width obtained.

Additional Embodiment

An additional embodiment of the subject invention, similar to the embodiment shown in Figure 57b, is illustrated in Figures 76a-76b. As will be seen, this embodiment depends upon the surface tension of the material which will cause it to form a meniscus within the discontinuity, therefore, causing the material to bridge over the discontinuity, at least in part, and achieve a higher part resolution, without requiring the use of thin fill layers.

However, the effect of the meniscuses can also be used in conjunction with the fill layers. Figure 57b illustrates the beneficial impact of the meniscuses when used in conjunction with the fill layers.

The embodiment here, on the other hand, is based solely on the meniscus effect, without explicitly requiring the use of thin fill layers. In those instances where the layer thicknesses of the structural layers is so great that a meniscus cannot effectively form without the generation of thin fill layers, then the example of Figure 36b is preferable. However, when the thickness of the structural layers is thin enough so that a reasonable meniscus will form without requiring thin fill layers, then the embodiment here is preferable since it entails less steps, and is therefore easier to implement.

Compared to the examples of Figures 56a-56d, and Figures 36a-36e, in Figures 76a-76c, like elements are referred to with like reference numerals.

Figure 76a illustrates meniscus 937 being formed in an up-facing discontinuity formed by layers 805 and 806. The particular order of formation of the layers and the meniscus is shown in Figure 76a by the circled numbers.

As shown, the first step is to form layer 805 while the working surface is at level L1. Next, layer 806 is formed after the working surface has been moved to level L2. At this level, the object surface bounded by edge 806' and extension region 805" is surrounded by untransformed material. Next, the level of the working surface is moved to level L3. As shown, because of the surface tension of the material, as the material recedes from above extension region 805", a meniscus 937 will remain in the discontinuity as shown. The next step is to expose the meniscus to the synergistic stimulation, thereby transforming it. The result is a smoothed over object surface which more closely matches the envelope 810 of the object representation.

Figure 76b illustrates the formation of the meniscus in down-facing regions. As shown, the first step is to form layer 806 while the working surface is a level L1. Next, the working surface is moved to level L2, and layer 805 is formed. Next, the working surface is moved down to level L3, and as shown, meniscus 937 will remain in the discontinuity. Finally, a portion of the meniscus is exposed and transformed by directing synergistic stimulation through already-formed layer 805 in a similar manner to that described previously with respect to the examples of Figures 56d and 56e. However, since the exact shape and size of the meniscus may not be known, an exposure will be given which will expose as much of the meniscus as possible without risking the passing of significant radiation through to material which is to remain unexposed. Again, the result is an object surface which more closely defines the envelope 810 of the object representation.

Figure 76c illustrates the formation of multiple meniscuses on top of each other to achieve even more discontinuity reduction. This is accomplished through multiple iterations of the processes described above with respect to Figures 76a and 76b. Figure 76c illustrates

the use of multiple iterations in an up-facing discontinuity, but multiple iterations are equally available for use in a down-facing discontinuity.

As illustrated, to begin the process, layer 805 is formed while the working surface is at level L1. Next, the working surface is moved to level L2, and layer 806 is formed. The working surface is then moved to L3 (which is coincidental with the previous level L1), and the meniscus 937a is formed, whereupon it is exposed and transformed. The working surface is then moved to at least level L4, and then to L5, whereupon meniscus 937b is formed over transformed meniscus 937a. Meniscus 937b is then exposed and transformed. Then, the working surface is moved to at least level L6, and then to L7. At this point, meniscus 937c has formed over already-transformed meniscus 937b. This is then exposed and transformed. As seen, compared to Figure 76a, multiple iterations of the above process results in even higher surface resolution compared to the envelope 810 of the object representation. Also, Figure 76c shows three iterations of the process illustrated in Figure 76a, but this example is not meant to be limiting, and any number of iterations are possible.

In all the above embodiments, it is preferable to keep the working surface at a constant distance from the scanning mirrors. Otherwise, the computational complexity of converting between the radial movement of the scanning mirrors and the linear movement of the beam along the working surface will be more complex.

Figures 77a-77f illustrate another embodiment of a method for smoothing out surface discontinuities using the meniscus effect. In these figures, like elements are referred to with like reference numerals.

In Figure 77a, the process begins. As indicated, structural layer 301 is formed at working surface 300.

In Figure 77b, the structural layer is down-dipped below the working surface, preferably by approximately 300 mils.

In Figure 77c, the structural layer is up-dipped, and thereby recoated in the manner described previously in preparation for the formation of layer 1302. Layer 1302 is then formed at the working surface.

In Figure 77d, the partially-formed part is super-elevated, preferably by 4 or 5 layer thicknesses as shown, to ensure rapid formation of meniscus 1303.

Next, in Figure 77e, the material in meniscus 1303 is solidified, preferably by positioning the laser beam utilizing an appropriate cure width compensation amount determined using the cure width compensation algorithm discussed in S.N. 331,644.

In Figure 77f, the partially-formed part is down-dipped to continue the process.

Figure 78 illustrates the beneficial effect of this embodiment on a part surface. In this example, the part was formed with 10 mil layers, and the surface is inclined at 45°. The left-most portion of the figure illustrates discontinuities which were not smoothed out with the meniscus effect, while the right-most portion illustrates discontinuities which were smoothed out.

As described at the outset, the above examples are illustrative only, and are not meant to be limiting.

While embodiments and applications of this invention have been shown and described, it should be apparent to those skilled in the art that many more modifications are possible without departing from the inventive concepts herein. The invention, therefore, is not to be restricted, except in the spirit of the appended claims.

Claims:

1. A method for forming a three-dimensional object from a material capable of selective physical transformation upon exposure to synergistic stimulation including slicing a representation of the object into a plurality of layer representations, comprising the steps of:

overlaying the object representation with a plurality of slicing planes spaced along a slicing dimension, wherein any two successive slicing planes of said plurality bounds a layer of said object representation, said bounded layers also being successively spaced along said slicing dimension;

corresponding each bounded layer of said object representation with the two successive slicing planes bounding said layer, said two successive planes comprising first and second slicing planes, the first slicing plane being situated lower along the slicing dimension than the second slicing plane;

forming intersection segments for each bounded layer of said object representation comprising intersections between the object representation and a first selected one of the first and second slicing planes bounding said layer;

forming projection segments for each bounded layer of said object representation comprising projections, onto a second selected one of the first and second slicing planes bounding said layer, of intersections between said object representation and a third selected one of the first and second slicing planes bounding said layer, which is different from said second selected one;

forming a layer boundary representation for each bounded layer of said object representation comprising a boolean union of the intersection segments and the projection segments for that bounded layer;

introducing the layer boundary representation for each bounded layer into the layer representation for that layer;

successively forming layers of said material; and

selectively exposing said layers of said material to said synergistic stimulation in accordance with said layer representations to form said three-dimensional object.

2. The method of claim 1 further comprising the steps of forming, for at least a first bounded layer spaced below a second bounded layer along the slicing dimension, an up-facing boundary representation comprising a boolean difference between the layer boundary for the first bounded layer and the layer boundary for the second bounded layer, and including the up-facing boundary representation in the layer representation for a fourth selected one of said first and second bounded layers.

3. The method of claim 1 further comprising the steps of forming, for at least a first bounded layer spaced above a second bounded layer along the slicing dimension, a down-facing boundary representation comprising a boolean difference between the layer boundary for the first bounded layer and the layer boundary for the second bounded layer, and including the down-facing boundary representation in the layer representation for a fourth selected one of said first and second bounded layers.

4. The method of claim 1 further comprising the steps of adjusting the layer boundary representation for at least one bounded layer by forming a boolean difference between the layer boundary representation and any down-facing layer representation for the bounded layer to obtain an adjusted layer boundary representation, and

including the adjusted layer boundary representation in the layer representation for the bounded layer.

5. An apparatus for forming a three-dimensional object from a material capable of selective physical transformation upon exposure to synergistic stimulation, including slicing a representation of the object into a plurality of layer representations, comprising:

at least one computer programmed to overlay the object representation with a plurality of slicing planes spaced along a slicing dimension, wherein any two successive slicing planes of said plurality bounds a layer of said object representation, said bounded layers also being successively spaced along said slicing dimension;

wherein said computer is further programmed to correspond each bounded layer of said object representation with the two successive slicing planes bounding said layer, said two successive planes comprising first and second slicing planes, the first slicing plane being situated lower along the slicing dimension than the second slicing plane;

wherein said computer is further programmed to form intersection segments for each bounded layer of said object representation comprising intersections between the object representation and a first selected one of the first and second slicing planes bounding said layer;

wherein said computer is further programmed to form projection segments for each bounded layer of said object representation comprising projections, along a second selected one of the first and second slicing planes bounding said layer, of intersections between said object representation and a third selected one of the first and second slicing planes bounding said layer which is different from said second selected one;

wherein said computer is further programmed to form a layer boundary representation for each bounded layer of said object representation comprising a boolean union of the intersection segments and the projection segments for that bounded layer;

wherein said computer is further programmed to include the layer boundary representation for each bounded layer into the layer representation for that layer;

means for successively forming layers of said material; and

means for selectively exposing said layers of material to said synergistic stimulation in accordance with said layer representations to form said three-dimensional object.

6. The apparatus of claim 5 wherein said computer is further programmed to form, for at least a first bounded layer spaced below a second bounded layer along the slicing dimension, an up-facing boundary representation comprising a boolean difference between the layer boundary for the first bounded layer and the layer boundary for the second bounded layer, and to include the up-facing boundary representation in the layer representation for a fourth selected one of said first and second bounded layers.

7. The apparatus of claim 5 wherein said computer is further programmed to form, for at least a first bounded layer spaced above a second bounded layer along the slicing dimension, a down-facing boundary representation comprising a boolean difference between the layer boundary for the first bounded layer and a layer boundary for the second bounded layer, and to include the down-facing boundary representation in the layer representation for a fourth selected one of said first and second bounded layers.

8. The apparatus of claim 5 wherein said computer is further programmed to adjust the layer boundary representation for at least one bounded layer by forming a boolean difference between the layer boundary representation and any down-facing layer representation for the bounded layer to obtain an adjusted layer boundary representation, and to include the adjusted layer boundary representation in the layer representation for the bounded layer.

9. A method for forming a three-dimensional object from a material capable of selective exposure to synergistic stimulation, including forming layer representations of layers of the object from layer boundary representations of those layers, comprising the following steps:

forming, for at least a first layer spaced below a second layer, the first and second layers having layer boundary representations, the boolean difference between the layer boundary representation of a first selected one of said first and second layers, and the layer boundary representation of a second selected one of said first and second layers different from said first selected one to form an outward-facing boundary representation for said first selected one of the first and second layers;

including the outward facing boundary representation in the layer representation of the first selected one of said first and second layers;

successively forming layers of said material; and

selectively exposing said layers of said material to said synergistic stimulation in accordance with said layer representations to form said three-dimensional object.

10. An apparatus for forming a three-dimensional object from a material capable of selective physical transformation upon exposure to synergistic stimulation,

including forming layer representations of layers of the object from layer boundary representations of those layers, comprising:

at least one computer programmed to form, for at least a first layer spaced below a second layer, the first and second layers having layer boundary representations, a boolean difference between the layer boundary representation of a first selected one of said first and second layers, and the layer boundary representation of a second selected one of said first and second layers, different from said first selected one, to form an outward-facing boundary representation for said first selected one of said first and second layers;

wherein said computer is further programmed to include the outward-facing boundary representation in the layer representation of the first selected one of said first and second layers;

means for successively forming layers of said material; and

means for selectively exposing said layers of said material to said synergistic stimulation in accordance with said layer representations to form said three-dimensional object.

11. A method of making an object, the object defining an object envelope, by stereolithography from layers of a medium, the medium having a minimum solidification depth and being solidifiable upon exposure to synergistic stimulation, comprising the steps of:

selecting an area element at an upper surface of a first layer of medium with the area element corresponding to a first cross-section of the object;

determining the thickness between the area element at the upper surface of the first layer of medium and the object envelope underlying the area element;

comparing the thickness to the minimum solidification depth;

increasing the thickness by creating one or more next layers of medium over the first layer, without exposing the area element of the first cross-section to synergistic stimulation, until the thickness equals or exceeds the minimum solidification depth; and

exposing the area element to synergistic stimulation to form at least a portion of the object.

12. A method of making an object by stereolithography from layers of a medium having a minimum solidification depth and solidifiable upon exposure to synergistic stimulation, comprising the steps of:

selecting a region of a first layer of medium having at least one of an up facing and a non-up-facing area element;

exposing any up facing area element to synergistic stimulation;

determining an uninterrupted thickness of the object at any non-up-facing area element from an upper surface of the first layer of medium to a lower object surface underlying any such area element;

creating a next layer over the first layer without exposing any non-up-facing area element to solidifying synergistic stimulation until the thickness below any such non-up-facing area element is not less than the minimum solidification depth; and

exposing any such non-up-facing area element to solidifying synergistic stimulation to form at least a portion of the object.

13. An improved method for stereolithographically forming a three-dimensional object from layers of a medium capable of physical transformation upon exposure to synergistic stimulation comprising the successive formation of

layers of said material and selectively exposing said layers sequentially to synergistic stimulation corresponding to successive cross-sections of the three-dimensional object to build up the three-dimensional object layer by layer, the improvement comprising: leaving untransformed material on at least one portion of one cross-section, at least until after that cross-section has been coated over with at least one layer of additional untransformed material, in preparation for formation of at least one successive layer of the object, wherein the at least one portion is transformed by exposure to synergistic stimulation through the material in the at least one layer of additional material that has been applied, to form at least a portion of the object.

14. An improved stereolithographic method for producing a three-dimensional object on substantially a layer by layer basis from a material curable in response to synergistic stimulation including th steps of forming successive layers of said material and for selectively applying said synergistic stimulation to said successive layers of said material to form said three-dimensinal object from a plurality of cured layers of material, the improvement comprisng the step of:

curing a balanced layer and then curing a balancing layer in relation to said balanced layer such that reverse curl of said balanced layer caused by said balancing layer substantially offsets curl of said balancaed layer caused by said balancing layer.

15. An improved stereolithographic apparatus for producing a three-dimensional object on substantially a layer by layer basis from a material curable in response to synergistic stimulation including means for forming successive layers of said material and means for selectively applying said synergistic stimulation to said successive layers of said material to form said three-

dimensional object from a plurality of cured layers of material, the improvement comprising:

means for curing a balanced layer and then curing a balancing layer in relation to said balanced layer such that reverse curl of said balanced layer caused by said balancing layer substantially offsets curl of said balanced layer caused by said balancing layer.

16. A method for reducing a surface discontinuity comprising a deviation between a region of a three-dimensional object surface and a desired object envelope, the region to comprise an end of a not yet formed first structural layer, and an extension region, the extension region to comprise at least a portion of a surface of a not yet formed second structural layer, the second structural layer to have an end which is to extend beyond an end of the first structural layer by the extension region, the ends to abut, at least in part, against the envelope, the surface of the second structural layer to contact, at least in part, a surface of the first structural layer, the method comprising the following steps:

containing a volume of flowable material, the material capable of selective physical transformation upon selective exposure to synergistic stimulation whereupon a working surface of said material is formed;

selectively exposing material at said working surface to a first exposure of said synergistic stimulation to form a first selected one of said first and second structural layers;

forming a layer of untransformed material over an upper surface of said first selected one, said upper surface comprising one of said surfaces of said first and second structural layers, whereupon an upper surface of said untransformed layer defines a new working surface;

selectively exposing said layer to a second exposure of said synergistic stimulation to form a second selected one of said first and second structural layers which is different from said first selected one, whereupon a lower surface of said second selected one, said lower surface comprising one of said surfaces of said first and second structural layers, is situated below said new working surface;

raising said first and second selected ones until said region is situated above said new working surface, whereupon a meniscus of said material forms in said region to define a new object surface in said region which at least in part reduces said discontinuity; and

selectively exposing said meniscus to a third exposure of said synergistic stimulation whereupon said meniscus substantially transforms.

17. An apparatus for reducing a surface discontinuity comprising a deviation between a region of a three-dimensional object surface and a desired object envelope, the region to comprise an end of a not yet formed first structural layer, and an extension region, the extension region to comprise at least a portion of a surface of a not yet formed second structural layer, the second structural layer to have an end which is to extend beyond an end of the first structural layer by the extension region, the ends to abut, at least in part, against the envelope, the surface of the second structural layer to contact, at least in part, a surface of the first structural layer, comprising:

a container containing a volume of flowable material, the material being capable of selective physical transformation upon selective exposure to synergistic stimulation whereupon a working surface of said material is formed;

a forming means including at least one computer programmed to modify said building representation, wherein said building representation specifies a first exposure of said synergistic stimulation to form a first selected one of said first and second structural layers in accordance with a building representation, and wherein said building representation further specifies selectively exposing said layer to a second exposure of said synergistic stimulation to form a second selected one of said first and second structural layers which is different from said first selected one, whereupon a lower surface of said second selected one is situated below said new working surface, to specify selectively exposing said meniscus to a third exposure of said synergistic stimulation whereupon said meniscus substantially transforms;

recoating means for forming a layer of untransformed material over an upper surface of said first selected one, whereupon an upper surface of said untransformed layer defines a new working surface;

wherein said recoating means is also raises said first and second selected ones until said region is situated above said new working surface, whereupon a meniscus of said material forms in said region to define a new object surface in said region which at least in part reduces said discontinuity; and

said forming means selectively exposing material at said working surface to said synergistic stimulation in accordance with said modified building representation.

18. A method for forming a three-dimensional object from a material capable of selective physical transformation upon exposure to synergistic stimulation, comprising the steps of:

modifying an object representation, specifying, at least in part, a first layer of the object adjacent to a second layer of the object, said first and second layers specified to have thickness, and specified to form a surface which deviates by a deviation from a desired object envelope, to obtain a modified object representation further specifying forming a third layer, specified to have a thickness less than the thickness of said first and second layers, and attaching said third layer to said surface to reduce said deviation;

successively forming layers of said material; and

selectively exposing said layers of material to said synergistic stimulation in accordance with said modified object representation to obtain said three-dimensional object.

19. An apparatus for forming a three-dimensional object from a material capable of selective physical transformation upon exposure to synergistic stimulation, comprising the steps of:

at least one computer programmed to modify an object representation specifying, at least in part, a first layer of the object adjacent to a second layer of the object, said first and second layers specified to have thicknesses, and specified to form a surface which deviates by a deviation from a desired object envelope, to obtain a modified object representation further specifying forming a third layer, specified to have a thickness less than the thicknesses of said first and second layers, and attaching said third layer to said surface to reduce said deviation;

means for successively forming layers of said material; and

means for selectively exposing said layers of material to said synergistic stimulation in accordance with said modified object representations to form said three-dimensional object.

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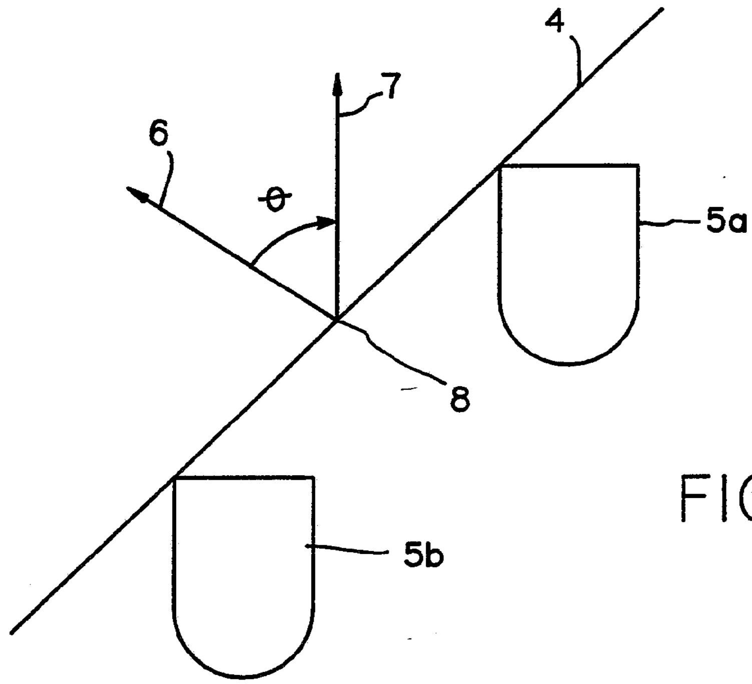


FIG. 1

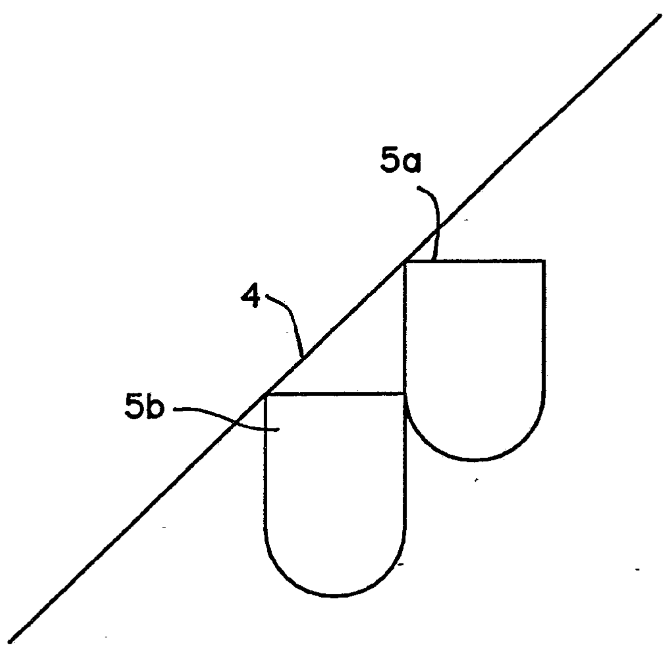


FIG. 2

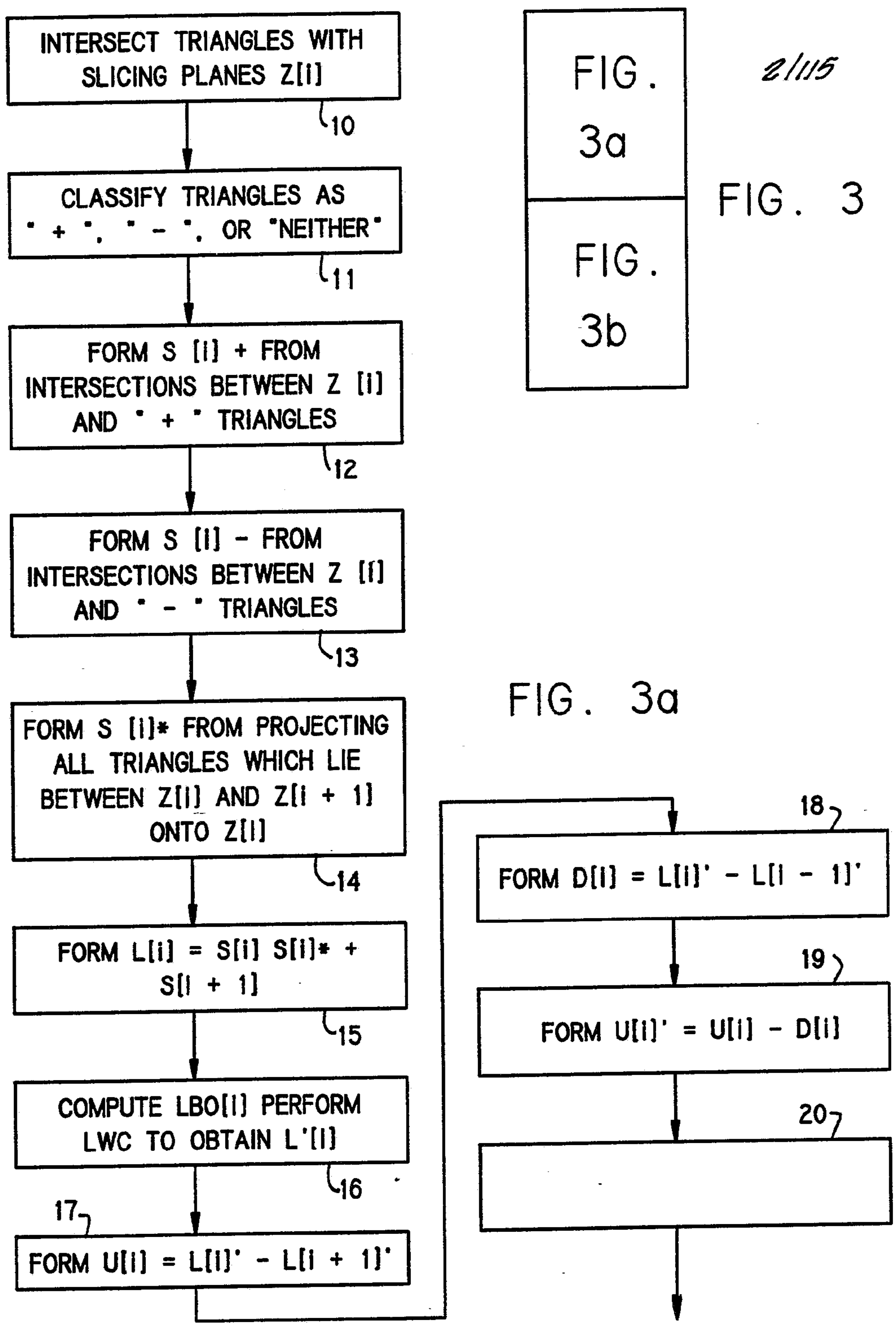

INTERSECT TRIANGLES WITH SLICING PLANES Z[I]
10
CLASSIFY TRIANGLES AS " + ", " - ", OR "NEITHER"
11
FORM S [I] + FROM INTERSECTIONS BETWEEN Z [I] AND " + " TRIANGLES
12
FORM S [I] - FROM INTERSECTIONS BETWEEN Z [I] AND " - " TRIANGLES
13
FORM S [I]* FROM PROJECTING ALL TRIANGLES WHICH LIE BETWEEN Z[I] AND Z[I + 1] ONTO Z[I]
14
FORM L[i] = S[I] S[I]* + S[I + 1]
15
COMPUTE LBO[I] PERFORM LWC TO OBTAIN L'[I]
16
17
FORM U[I] = L[I]' - L[I + 1]'
18
FORM D[I] = L[I]' - L[I - 1]'
19
FORM U[I]' = U[I] - D[I]
20
FIG. 3a
FIG. 3b

FIG. 3

FIG. 3a

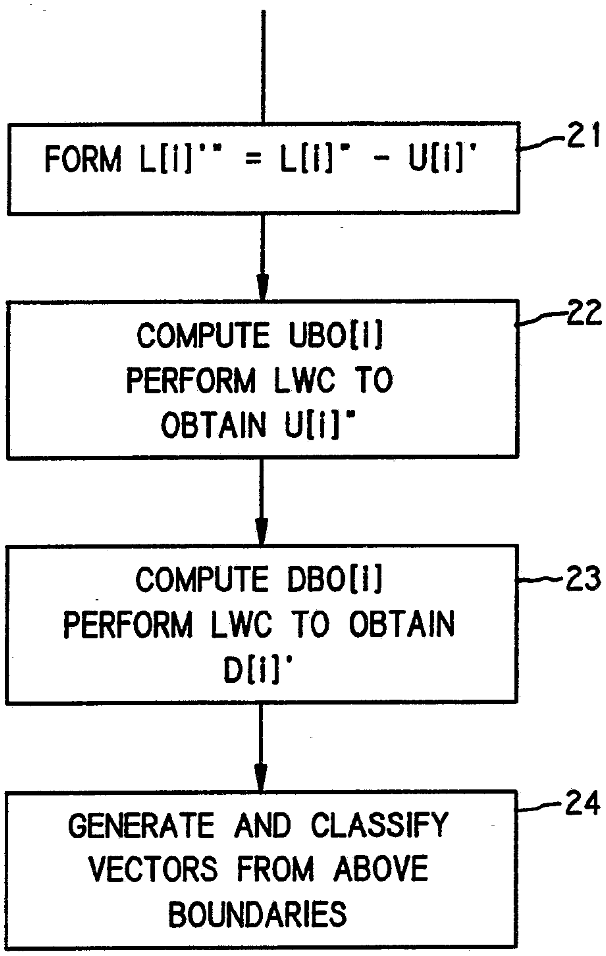

FORM L[i]''' = L[i]'' - U[i]'
21
COMPUTE UBO[i]
PERFORM LWC TO
OBTAIN U[i]''
22
COMPUTE DBO[i]
PERFORM LWC TO OBTAIN
D[i]'
23
GENERATE AND CLASSIFY
VECTORS FROM ABOVE
BOUNDARIES
24

FIG. 3b

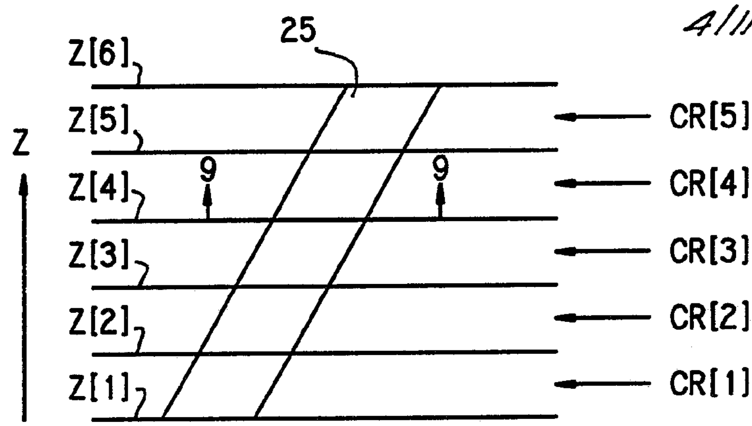


FIG. 4

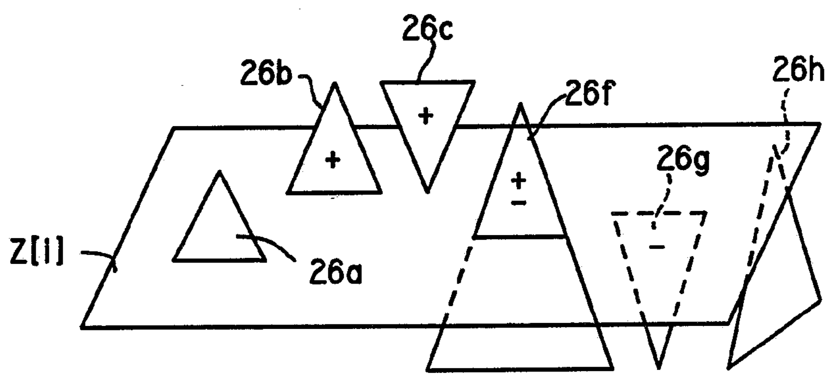


FIG. 5

FIG. 6

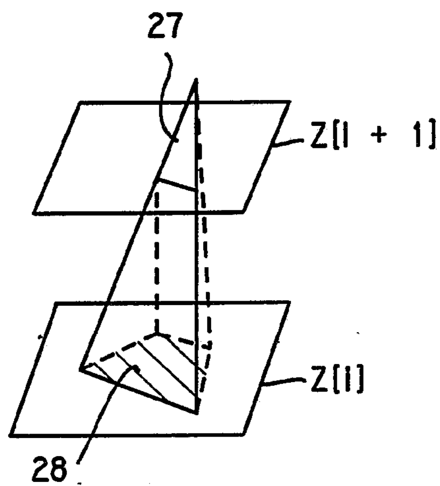


FIG. 7

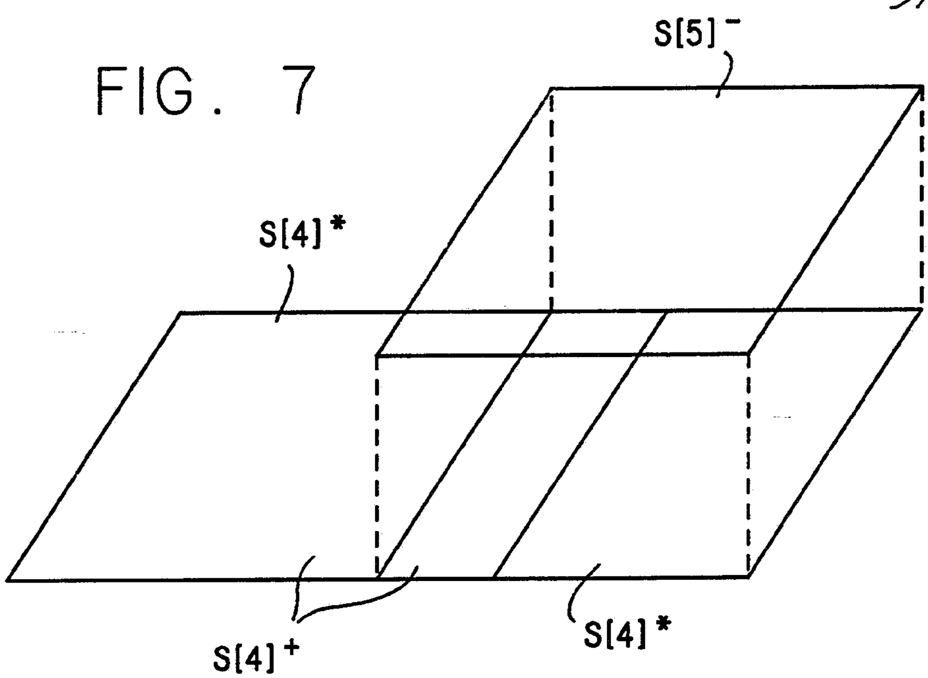


FIG. 8

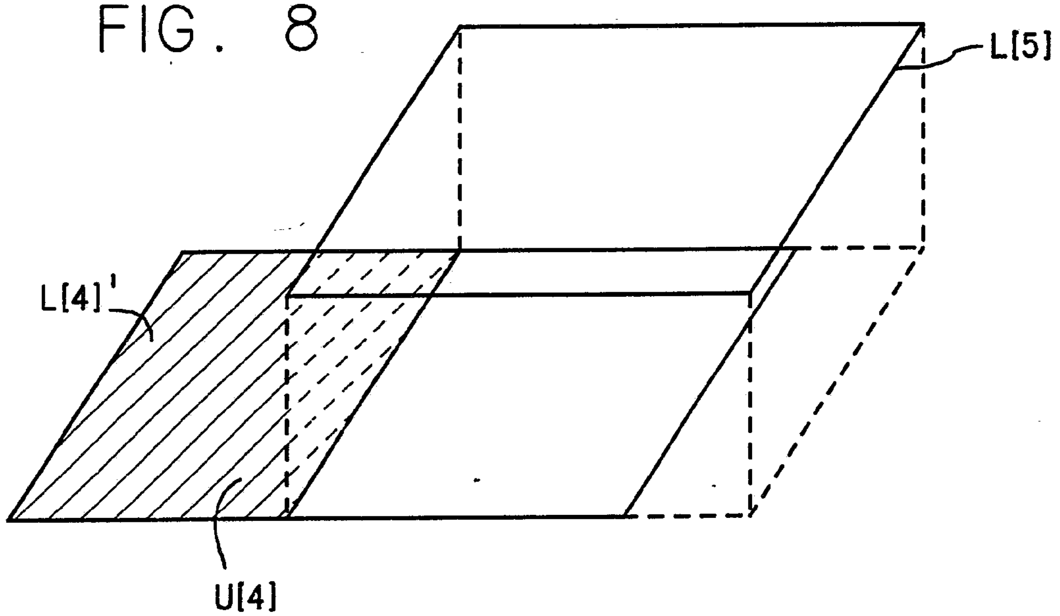


FIG. 9

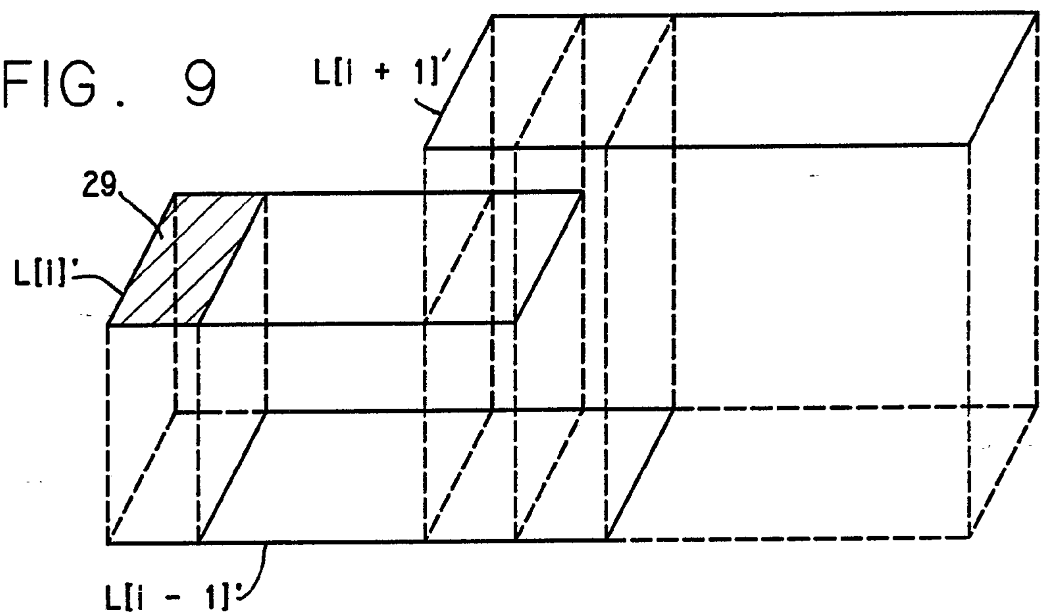


FIG. 11

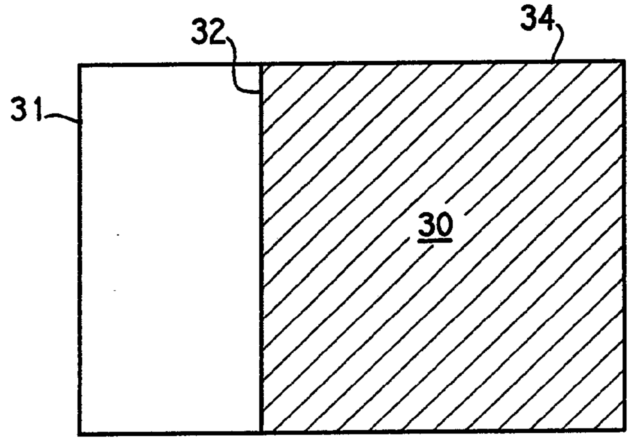
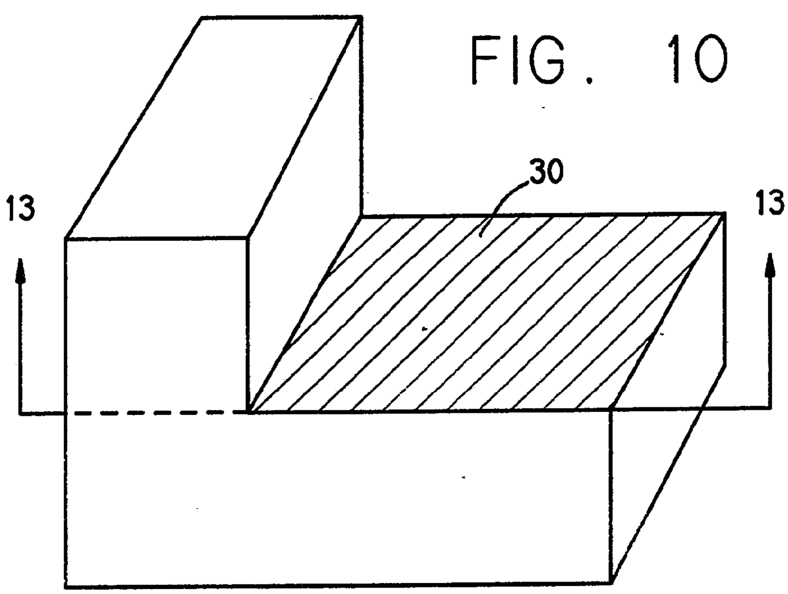


FIG. 10



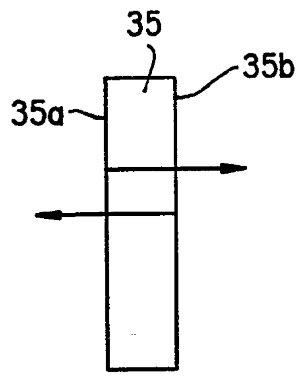


FIG. 12a

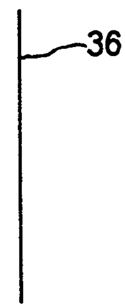


FIG. 12b

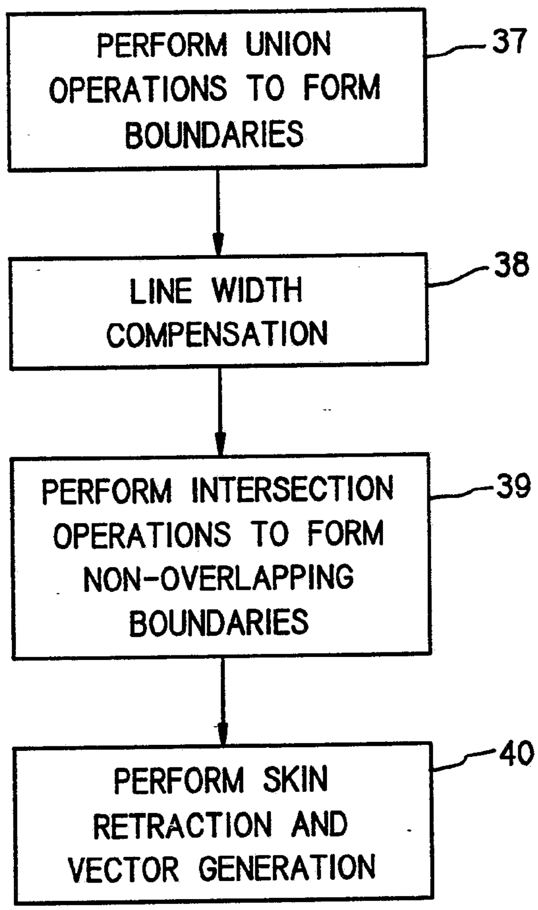


FIG. 13

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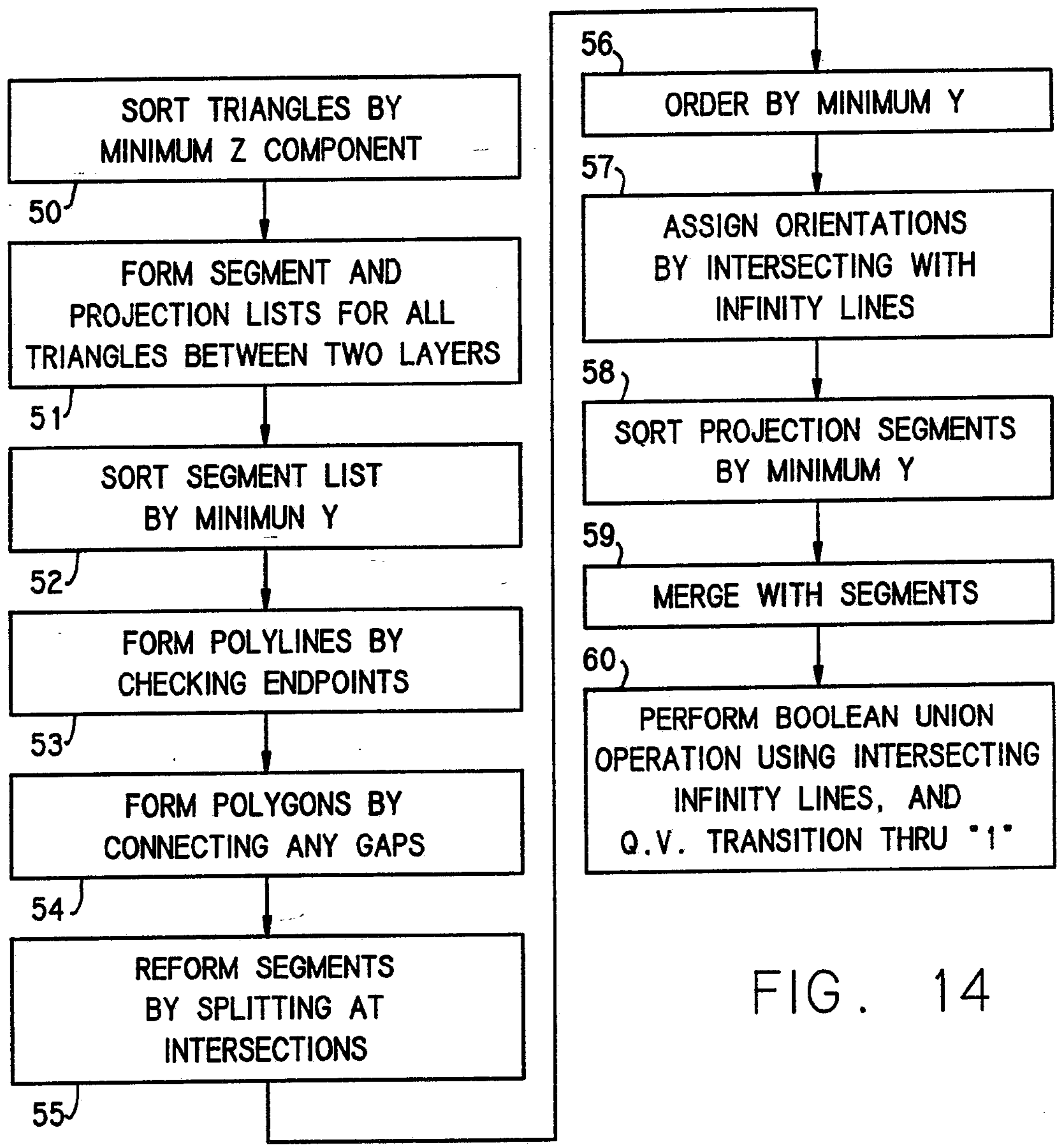
SORT TRIANGLES BY MINIMUM Z COMPONENT
50
FORM SEGMENT AND PROJECTION LISTS FOR ALL TRIANGLES BETWEEN TWO LAYERS
51
SORT SEGMENT LIST BY MINIMUN Y
52
FORM POLYLINES BY CHECKING ENDPOINTS
53
FORM POLYGONS BY CONNECTING ANY GAPS
54
REFORM SEGMENTS BY SPLITTING AT INTERSECTIONS
55
56
ORDER BY MINIMUM Y
57
ASSIGN ORIENTATIONS BY INTERSECTING WITH INFINITY LINES
58
SORT PROJECTION SEGMENTS BY MINIMUM Y
59
MERGE WITH SEGMENTS
60
PERFORM BOOLEAN UNION OPERATION USING INTERSECTING INFINITY LINES, AND Q.V. TRANSITION THRU "1"

FIG. 14

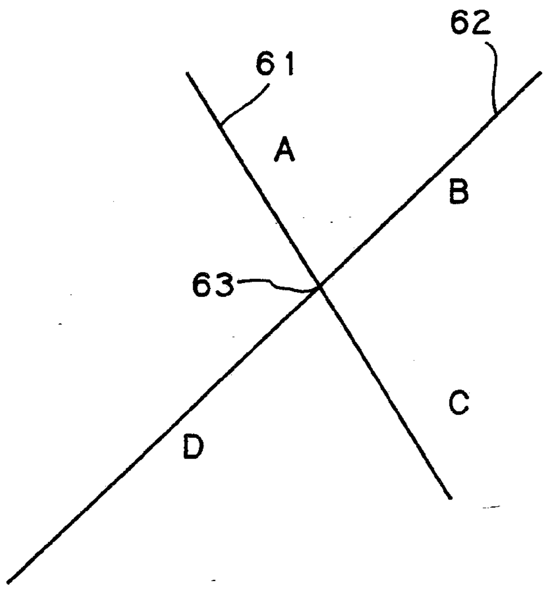

FIG. 15a

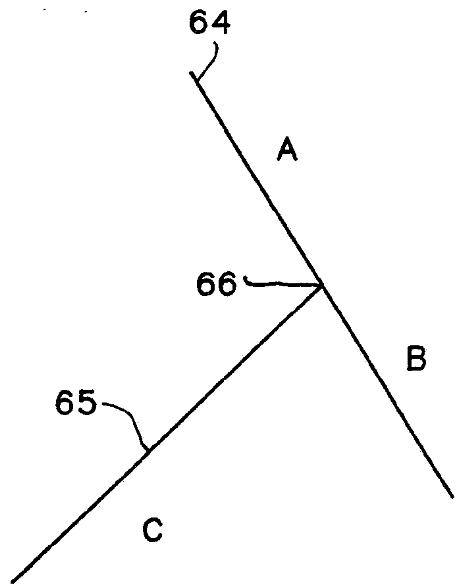

FIG. 15b

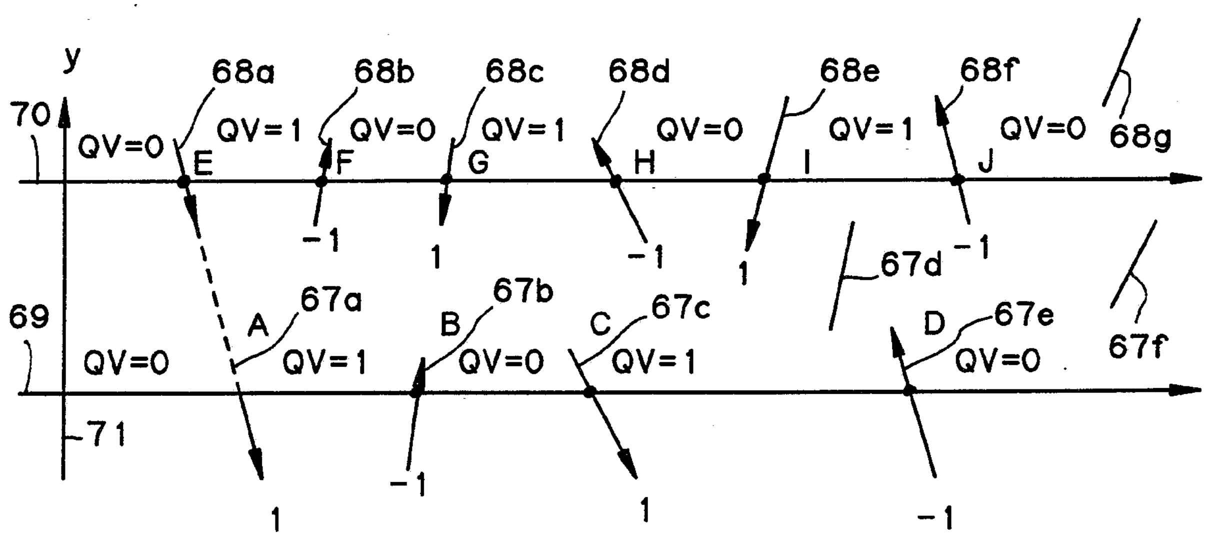

FIG. 16

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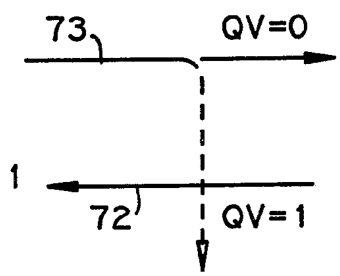


FIG. 17a

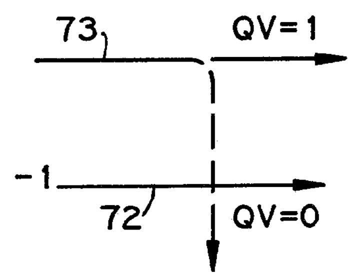
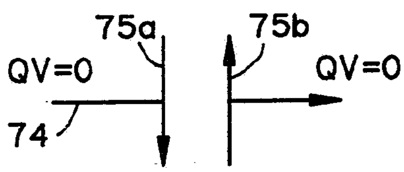
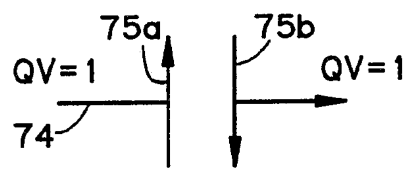


FIG. 17b



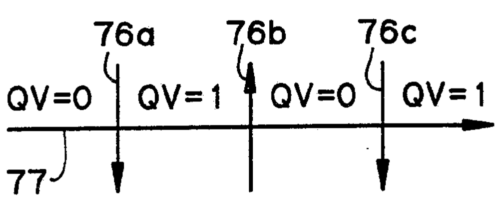
ORIENTATION = 0
BIORIENTATION = 2

FIG. 18a



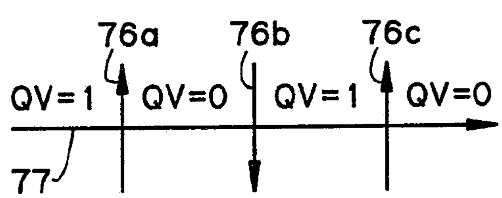
ORIENTATION = 0
BIORIENTATION = 2

FIG. 18b



ORIENT = 1
BIORIENT = 3

FIG. 19a



ORIENT = 1
BIORIENT = 3

FIG. 19b

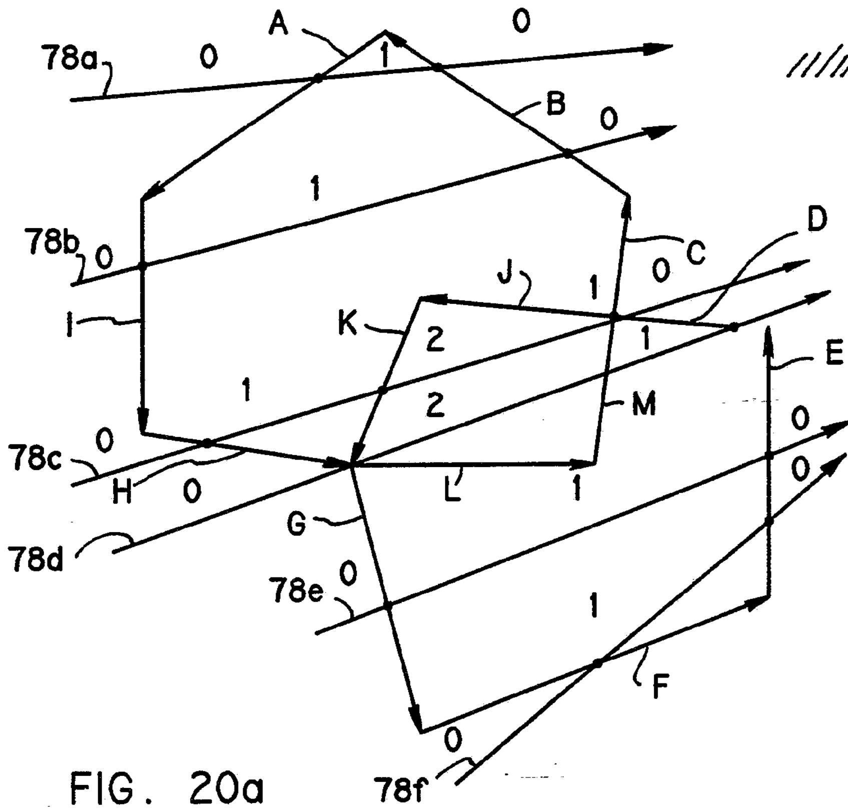


FIG. 20a

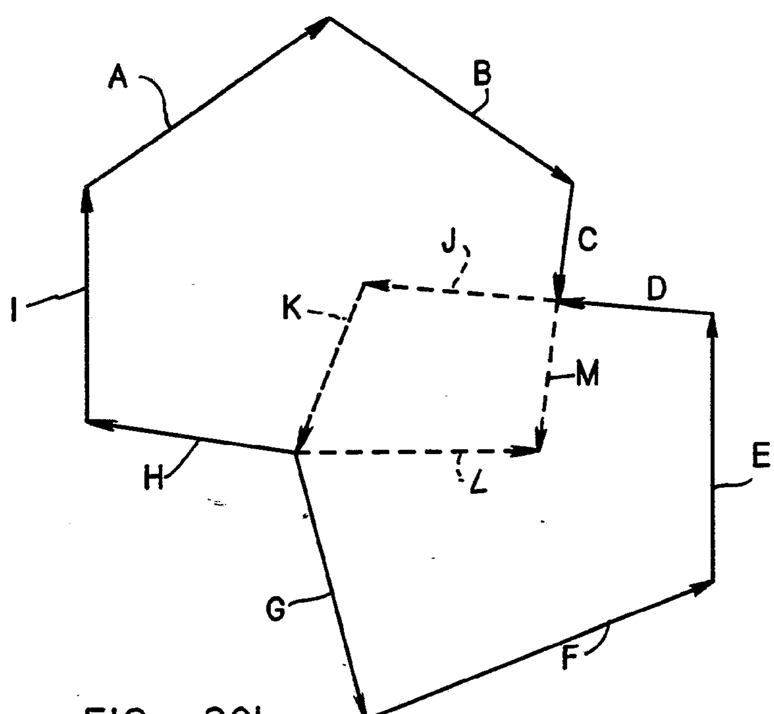


FIG. 20b

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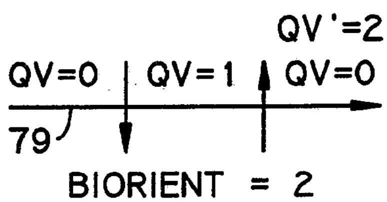


FIG. 21a

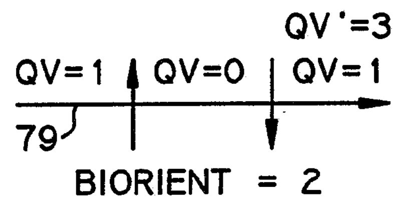


FIG. 21b

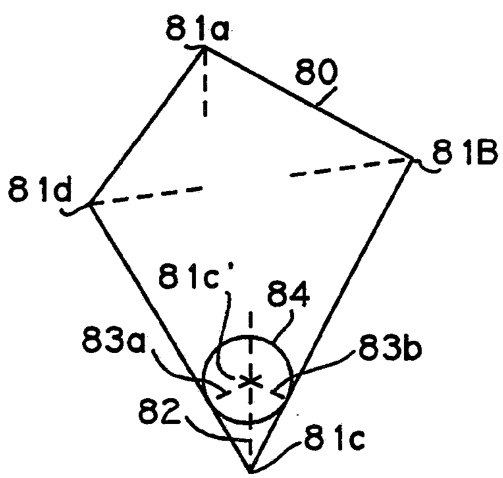


FIG. 22a

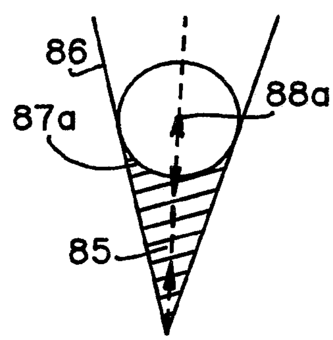


FIG. 22b

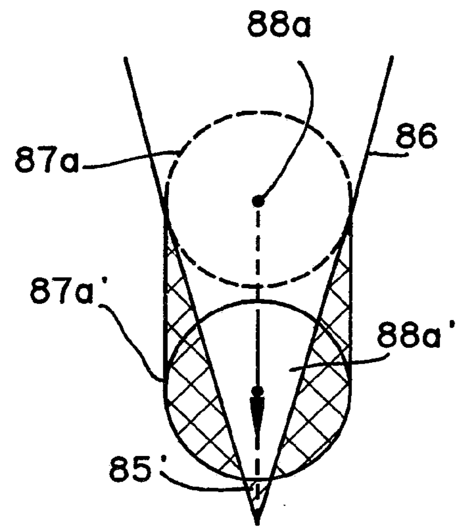


FIG. 22c

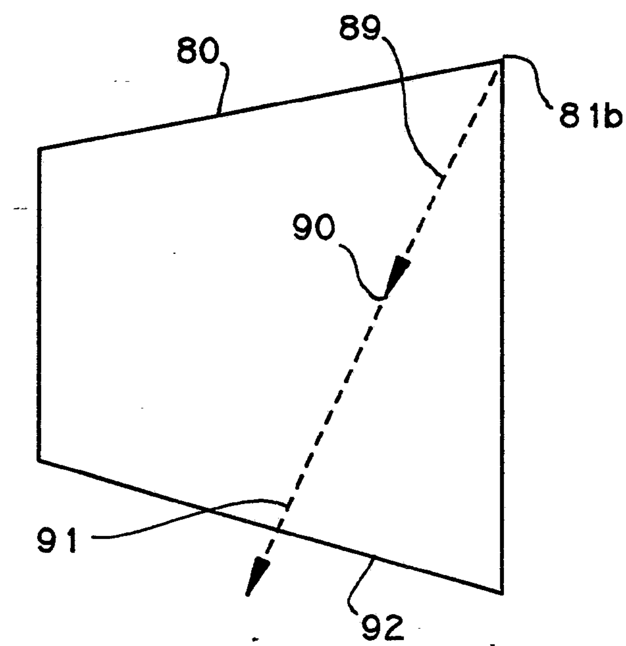


FIG. 22d

FIG. 22e

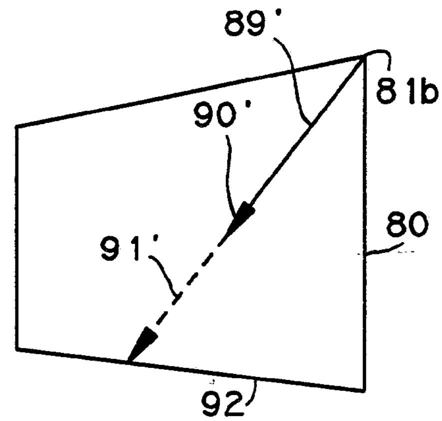


FIG. 22f

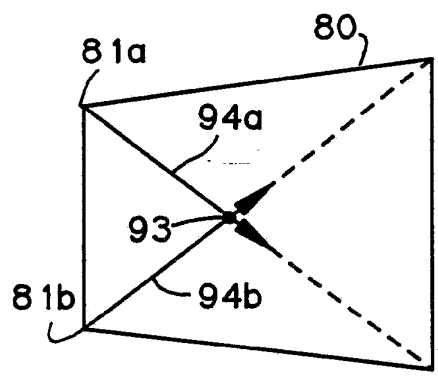


FIG. 22g

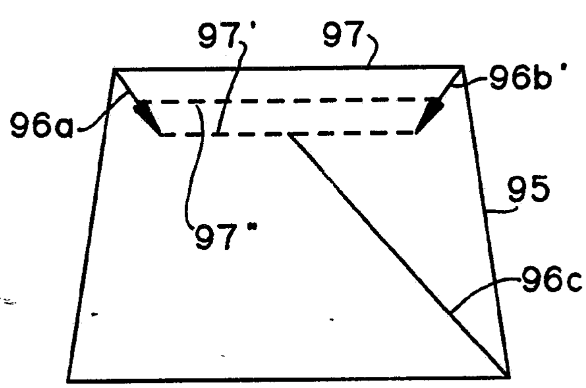
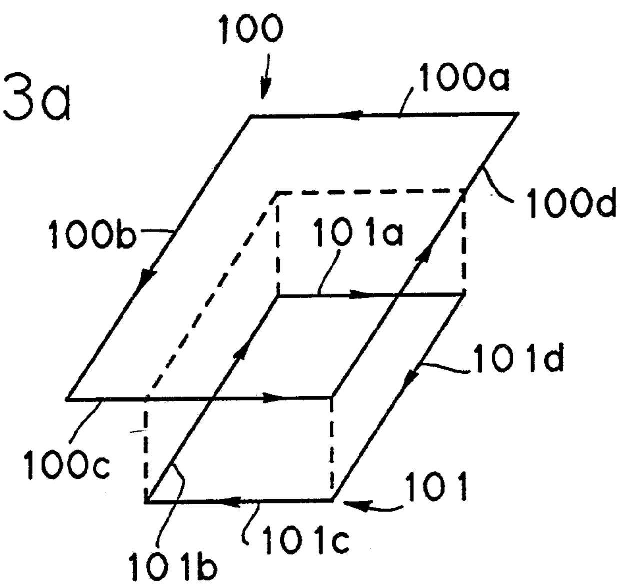


FIG. 23a



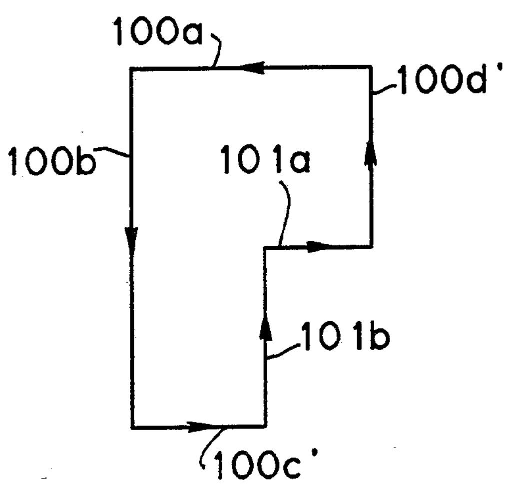
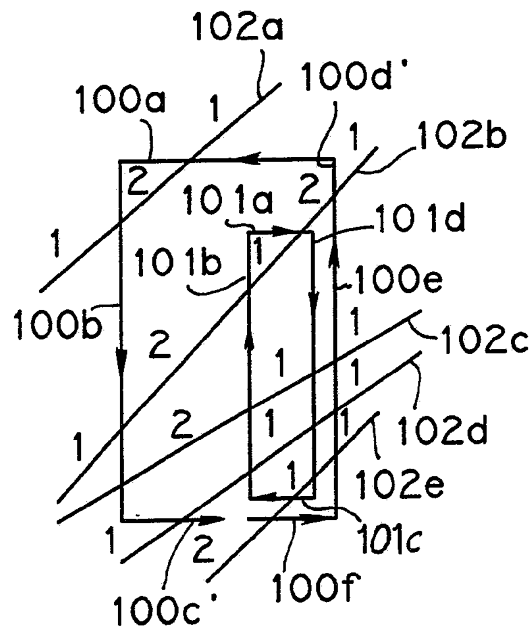


FIG. 23c

FIG. 23b



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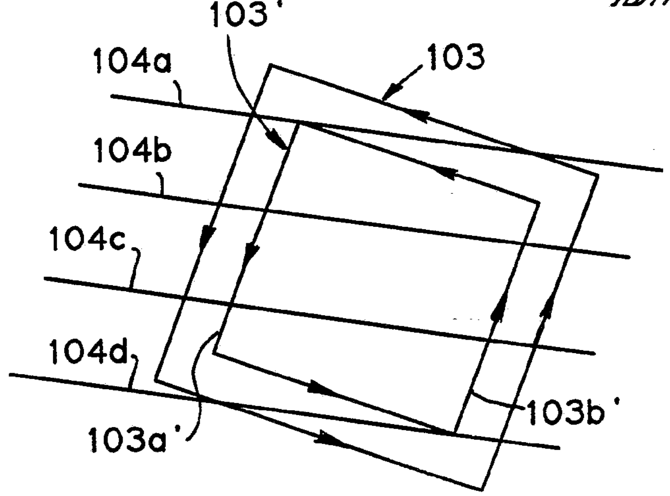


FIG. 24a

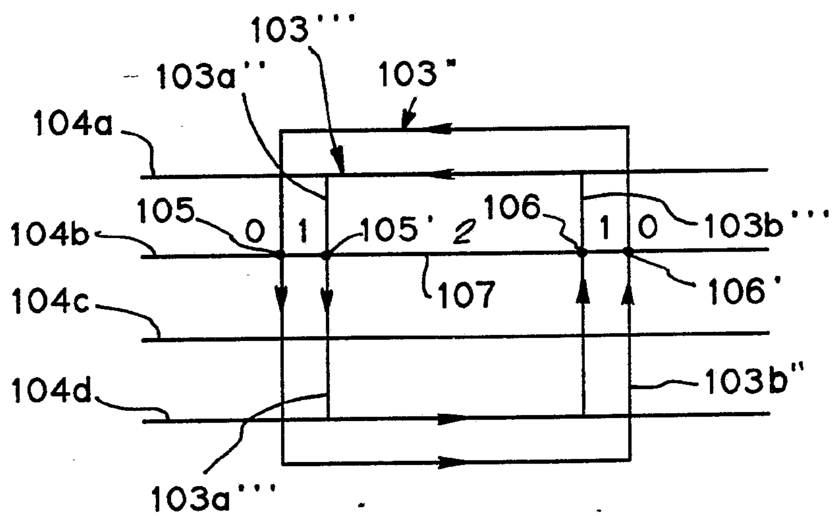


FIG. 24b

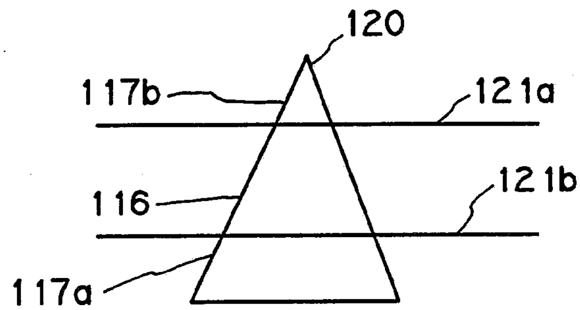
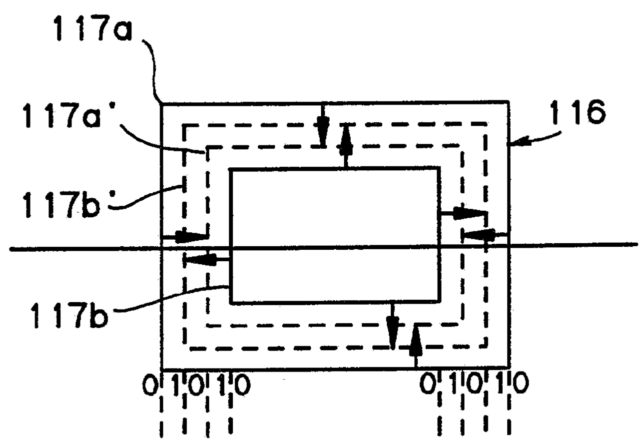


FIG. 25a

FIG. 25b



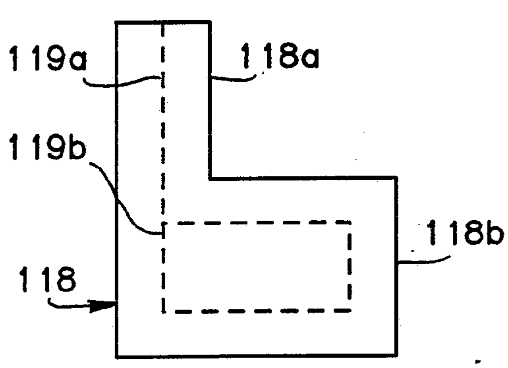


FIG. 25c

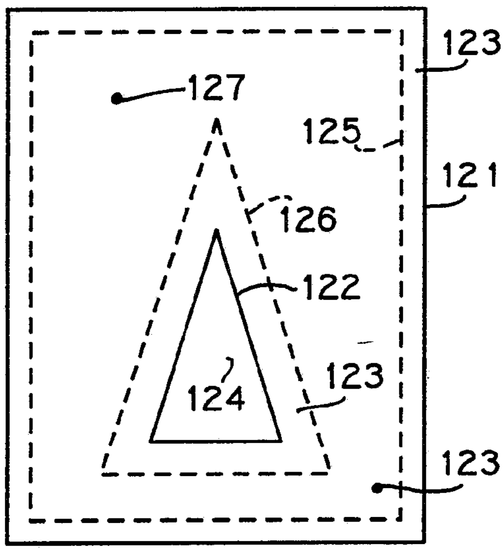


FIG. 26a

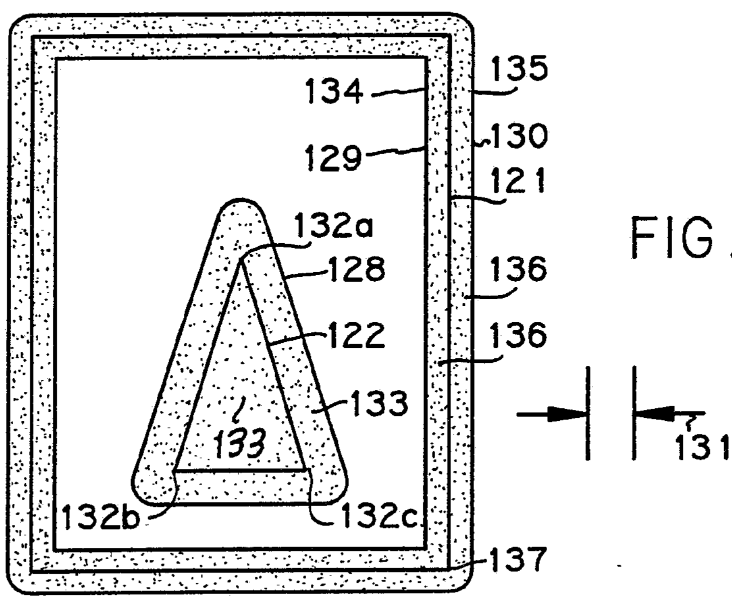


FIG. 26b

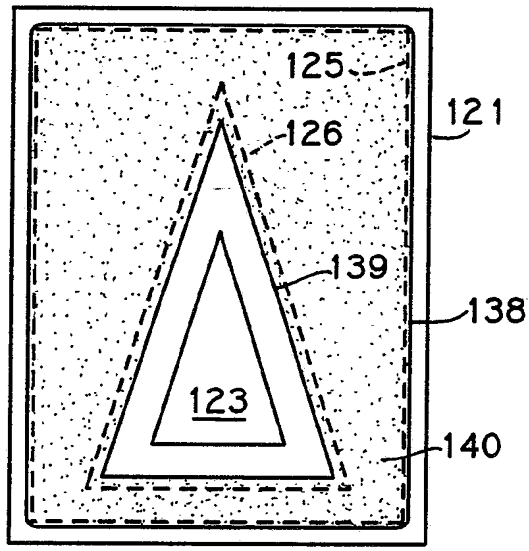


FIG. 26c

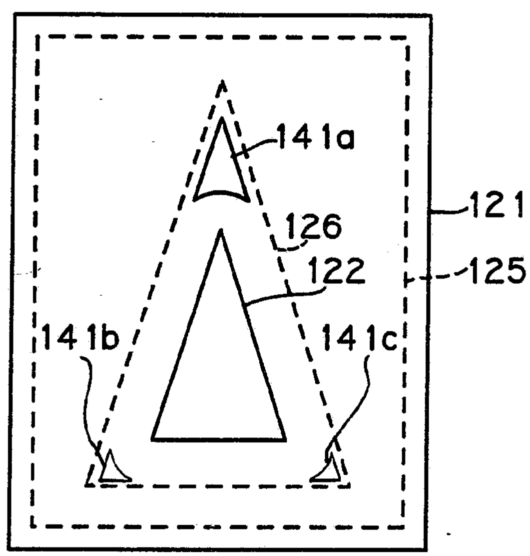


FIG. 26d

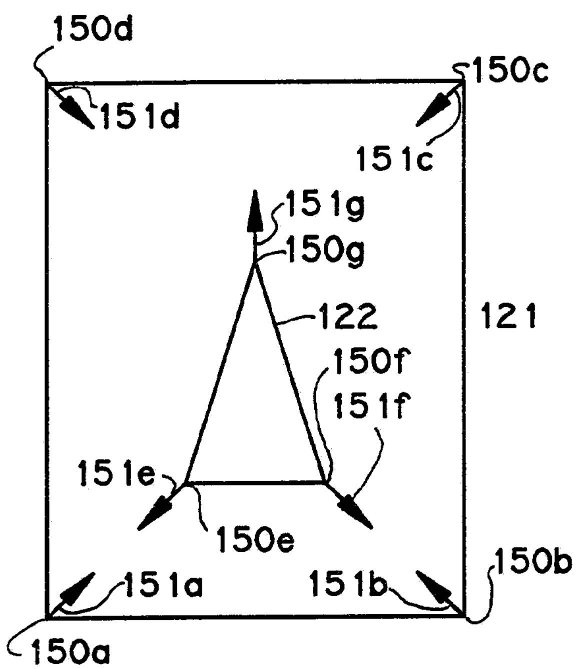


FIG. 27a

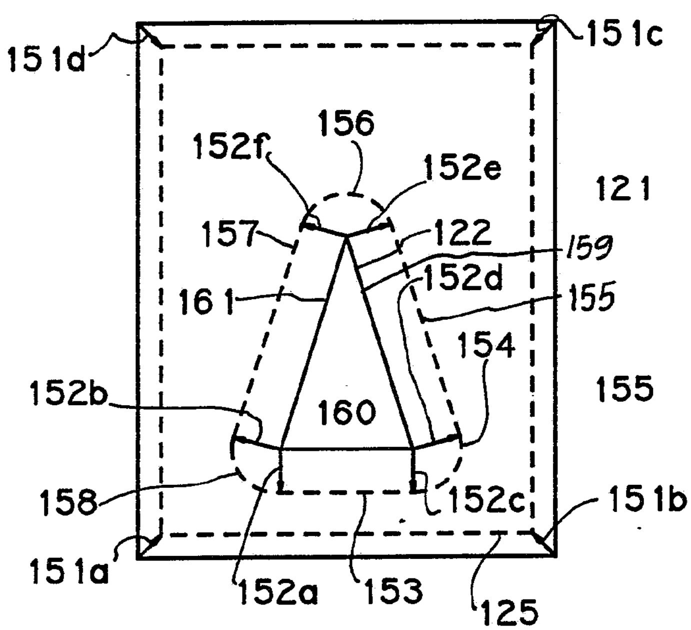


FIG. 27b

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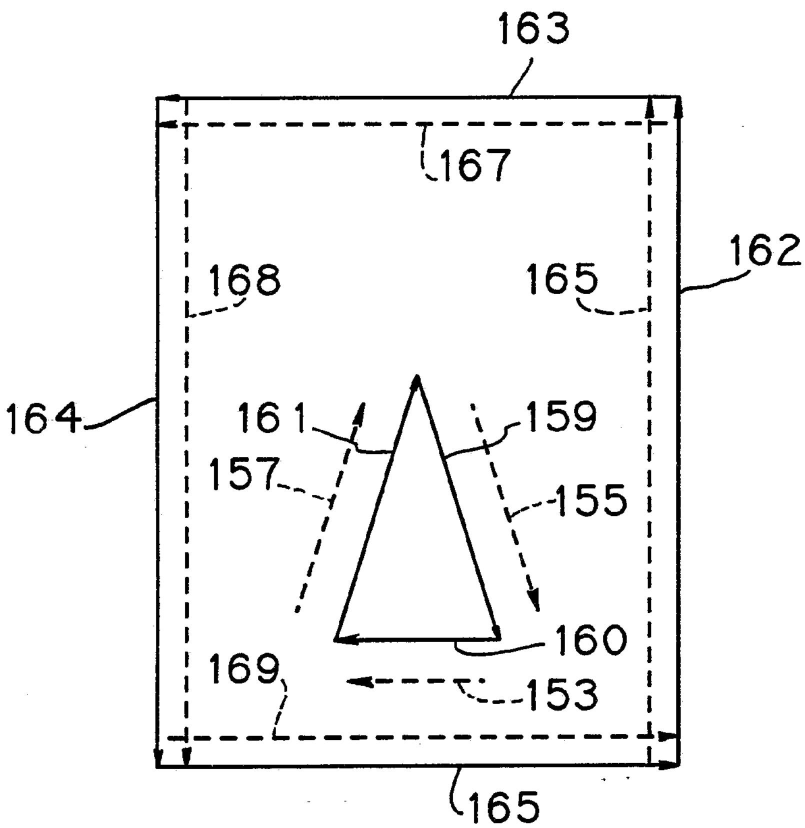

FIG. 27c

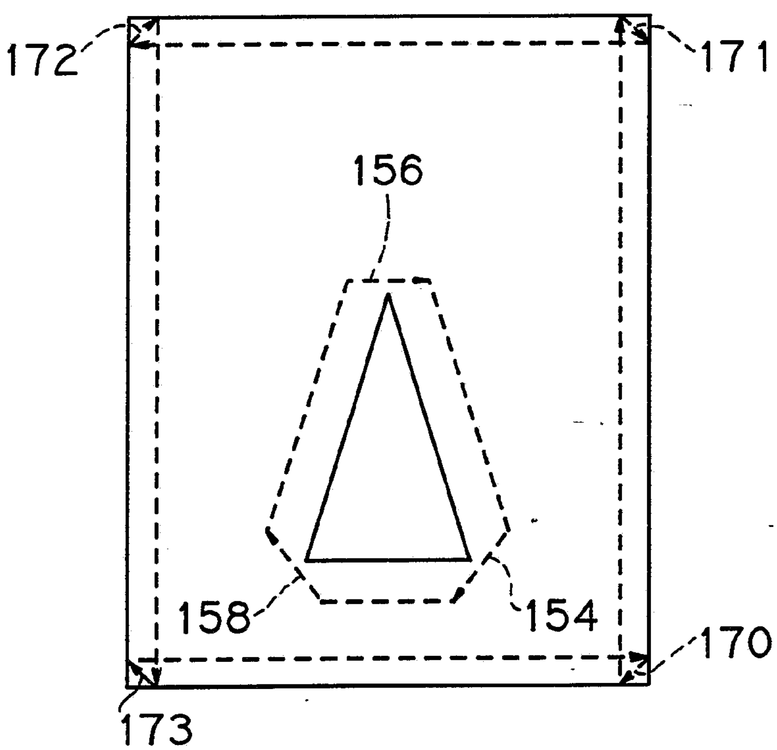

FIG. 27d

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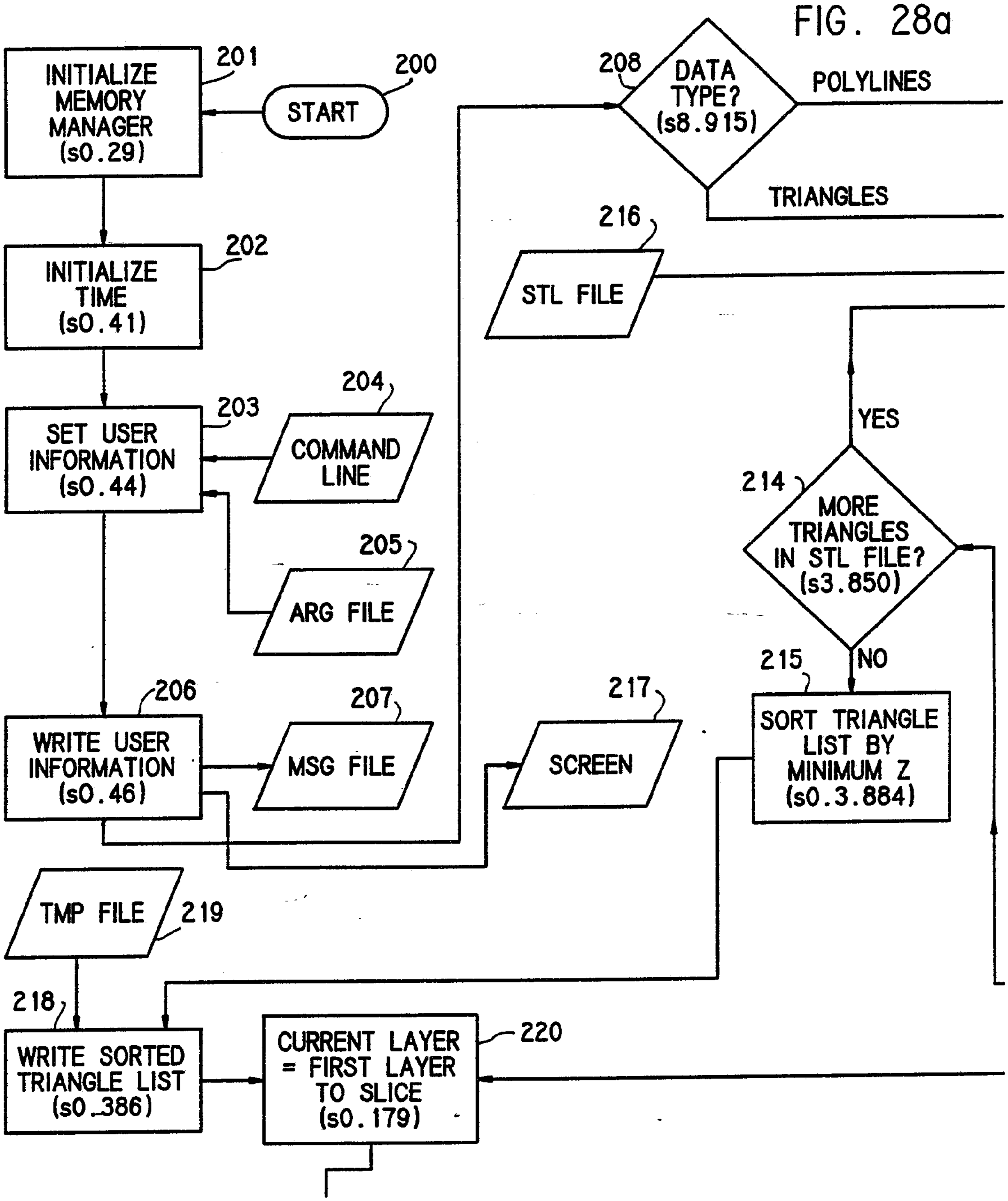
FIG. 28a



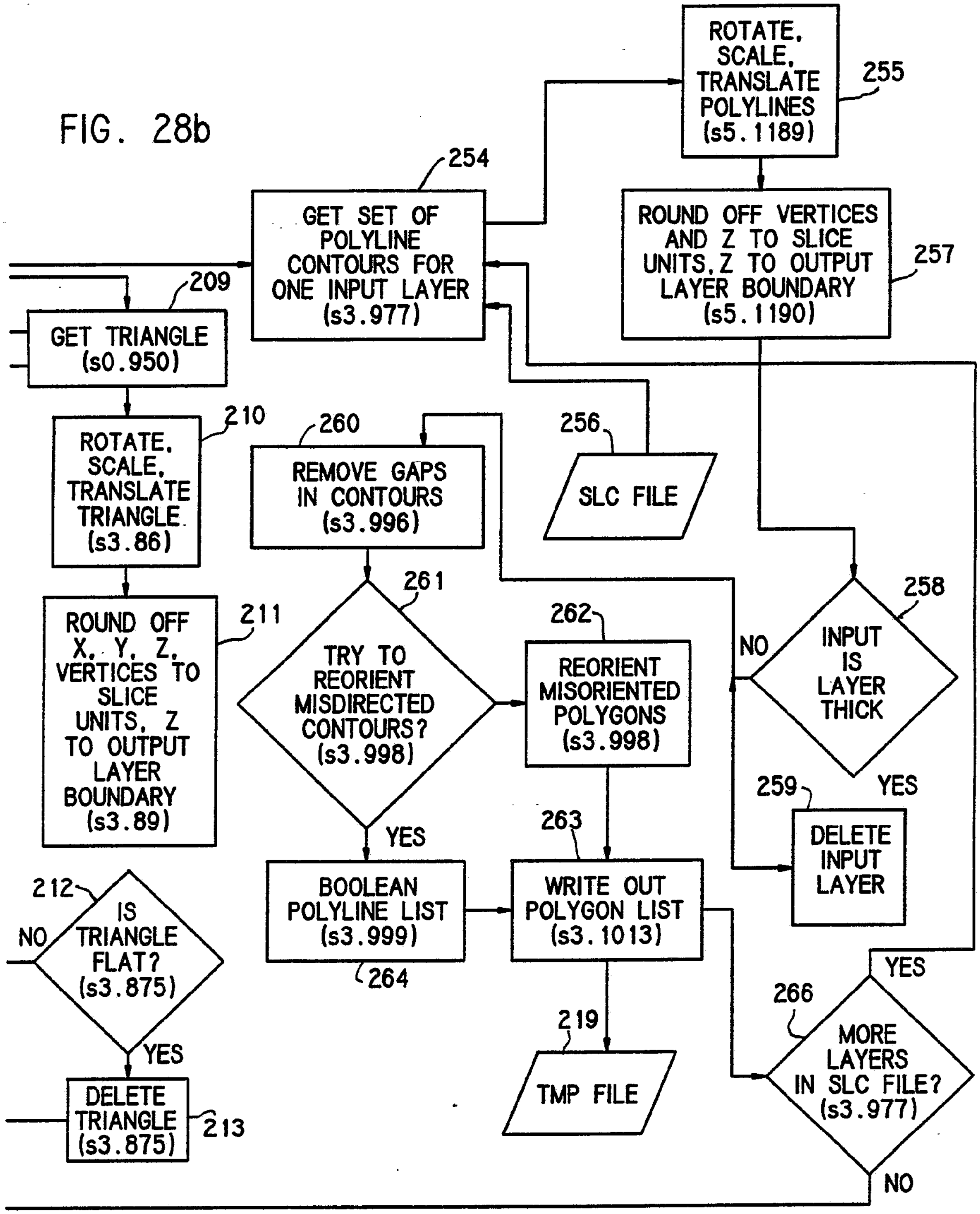

ROTATE, SCALE, TRANSLATE POLYLINES (s5.1189)
255
254
GET SET OF POLYLINE CONTOURS FOR ONE INPUT LAYER (s3.977)
ROUND OFF VERTICES AND Z TO SLICE UNITS, Z TO OUTPUT LAYER BOUNDARY (s5.1190)
257
209
GET TRIANGLE (s0.950)
210
ROTATE, SCALE, TRANSLATE TRIANGLE (s3.86)
260
REMOVE GAPS IN CONTOURS (s3.996)
256
SLC FILE
261
ROUND OFF X, Y, Z, VERTICES TO SLICE UNITS, Z TO OUTPUT LAYER BOUNDARY (s3.89)
211
TRY TO REORIENT MISDIRECTED CONTOURS? (s3.998)
262
REORIENT MISORIENTED POLYGONS (s3.998)
258
NO
INPUT IS LAYER THICK
YES
259
DELETE INPUT LAYER
YES
263
BOOLEAN POLYLINE LIST (s3.999)
264
WRITE OUT POLYGON LIST (s3.1013)
212
IS TRIANGLE FLAT? (s3.875)
NO
YES
DELETE TRIANGLE (s3.875)
213
219
TMP FILE
YES
266
MORE LAYERS IN SLC FILE? (s3.977)
NO

FIG. 28b

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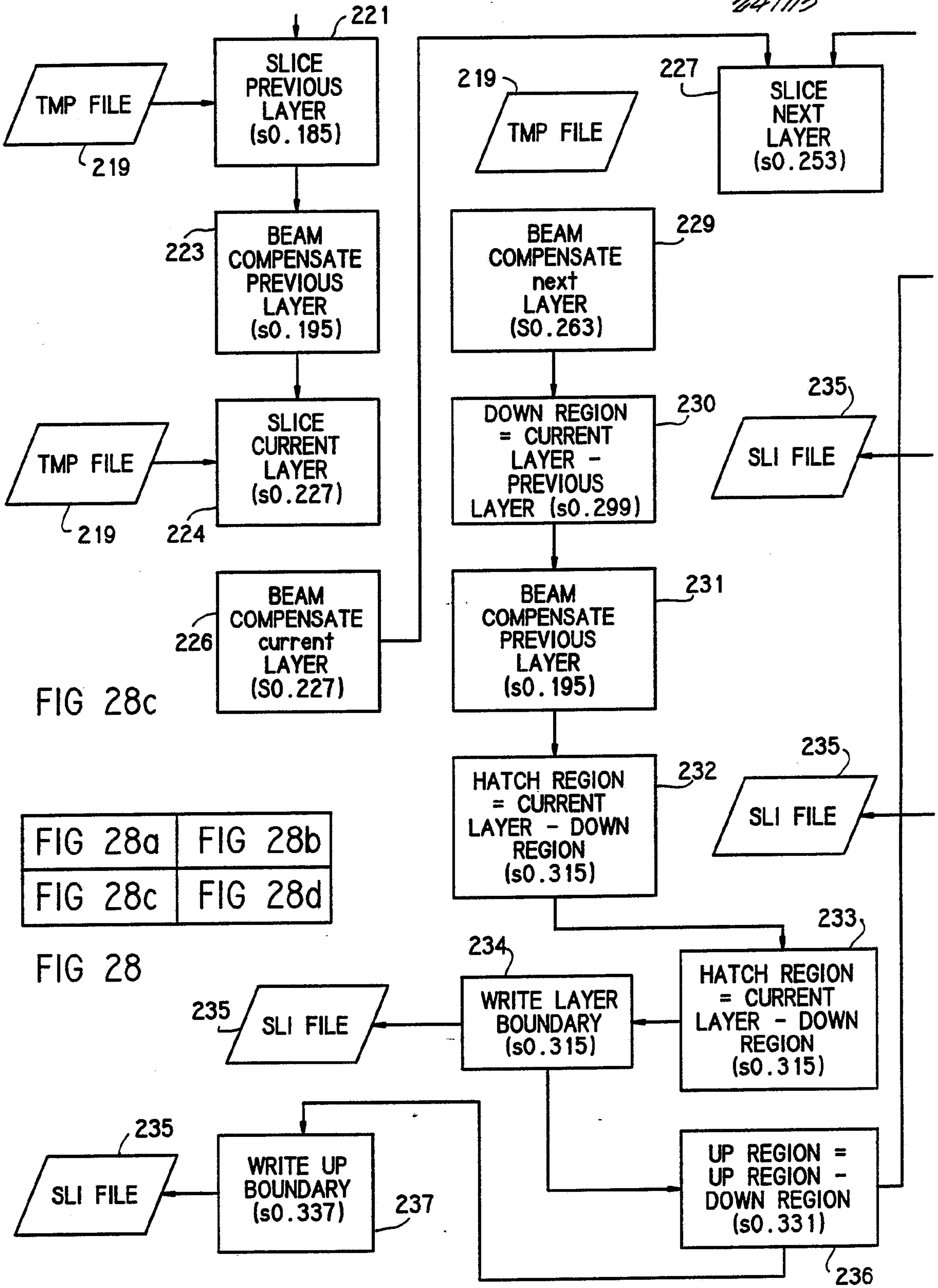

FIG 28c

FIG 28a	FIG 28b
FIG 28c	FIG 28d

FIG 28

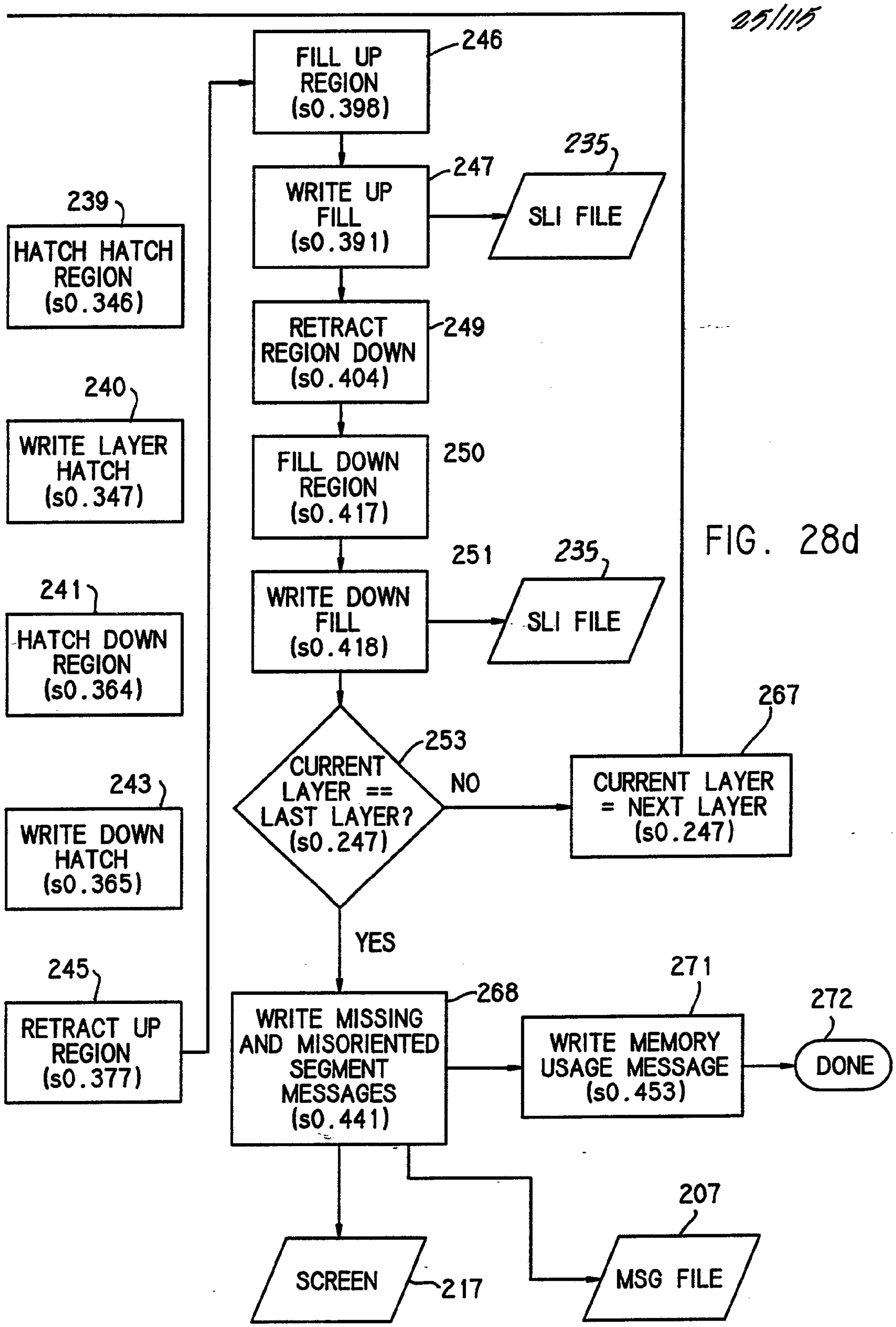
FILL UP REGION (s0.398)
246
WRITE UP FILL (s0.391)
247
SLI FILE
235
HATCH HATCH REGION (s0.346)
239
RETRACT REGION DOWN (s0.404)
249
WRITE LAYER HATCH (s0.347)
240
FILL DOWN REGION (s0.417)
250
HATCH DOWN REGION (s0.364)
241
WRITE DOWN FILL (s0.418)
251
SLI FILE
235
CURRENT LAYER == LAST LAYER? (s0.247)
253
NO
CURRENT LAYER = NEXT LAYER (s0.247)
267
WRITE DOWN HATCH (s0.365)
243
YES
RETRACT UP REGION (s0.377)
245
WRITE MISSING AND MISORIENTED SEGMENT MESSAGES (s0.441)
268
WRITE MEMORY USAGE MESSAGE (s0.453)
271
DONE
272
SCREEN
217
MSG FILE
207

FIG. 28d

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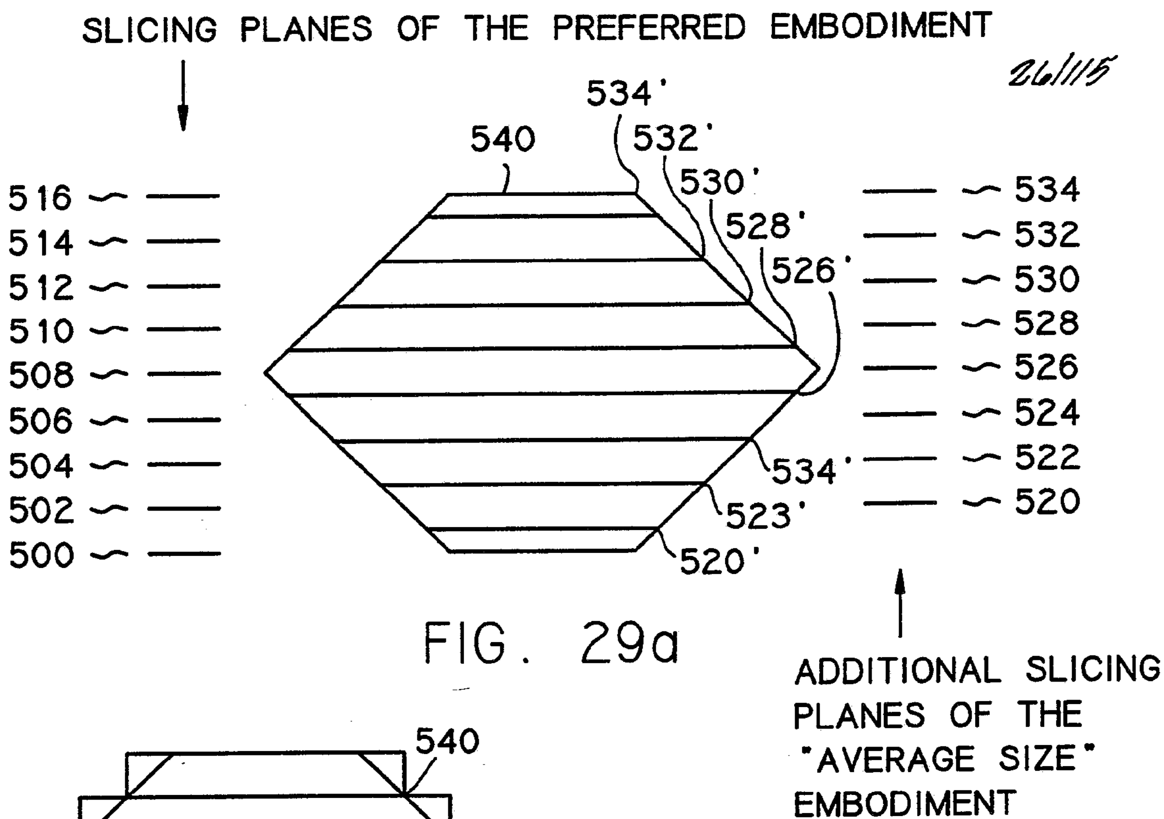


FIG. 29a

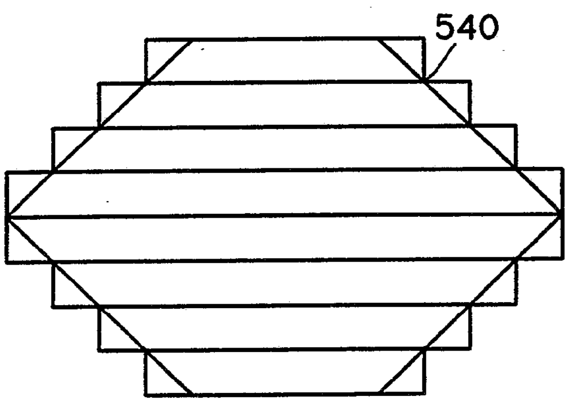


FIG. 29b

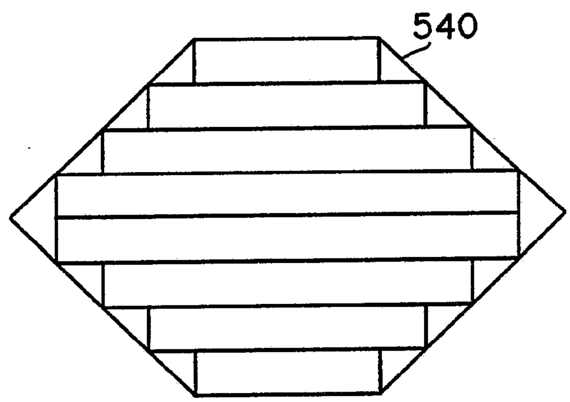


FIG. 29c

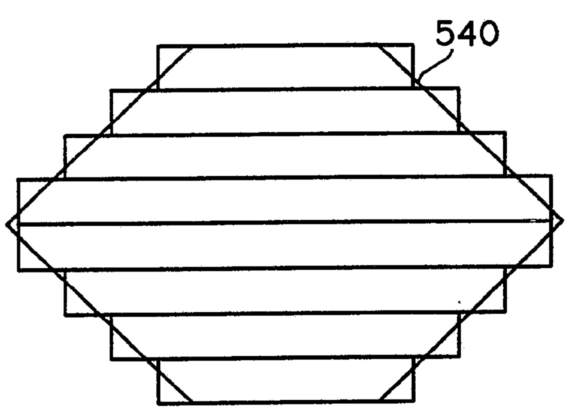


FIG. 29d

DETERMINATION OF HOW TO COMPENSATE VECTORS IF DESIRED TO BE DONE AFTER FORMATION OF FINAL REGIONS

LAYER I - 1

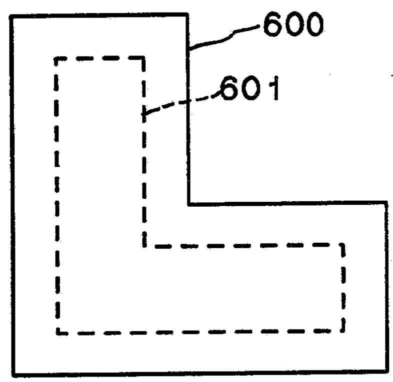
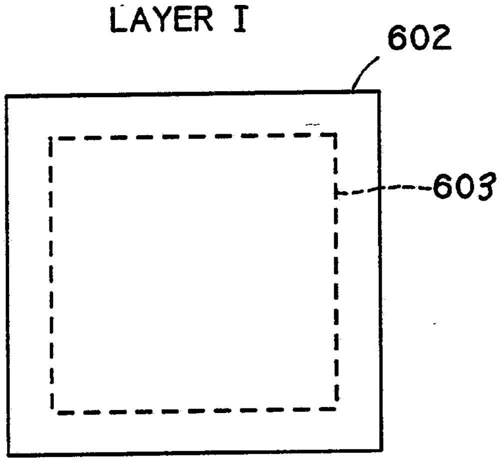


FIG. 30a

BEAM COMP ON INITIAL BOUNDARY

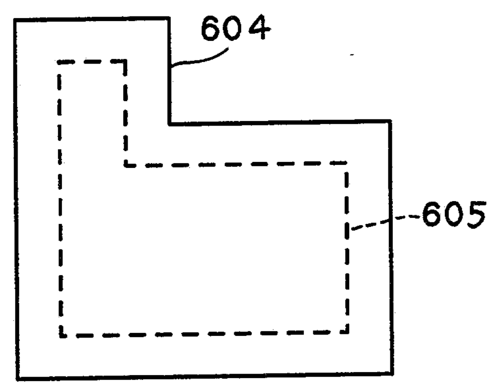
LAYER I



BEAM COMP ON INITIAL BOUNDARY

FIG. 30b

LAYER I + 1



BEAM COMP ON INITIAL BOUNDARY

FIG. 30c

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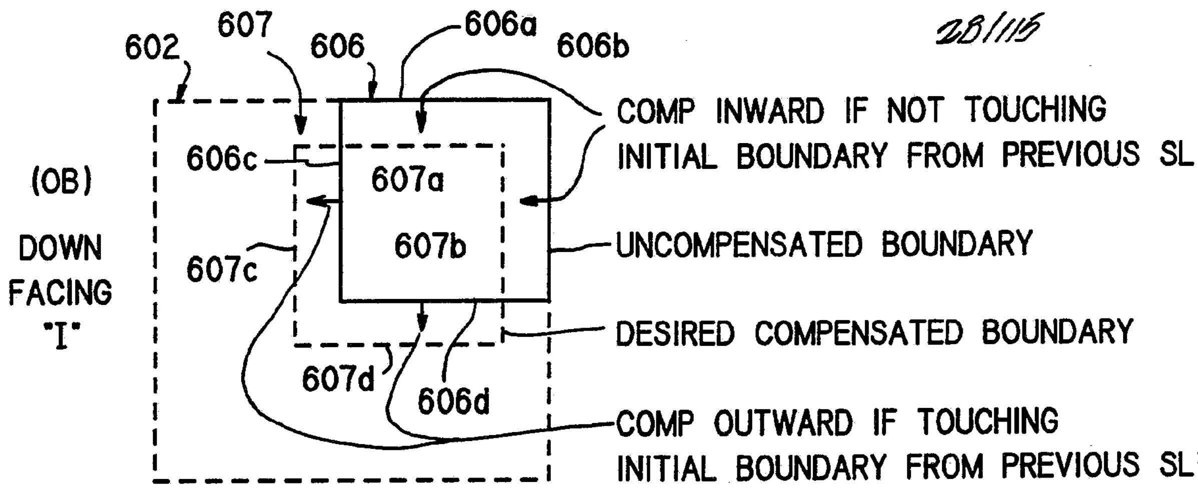

FIG. 30d

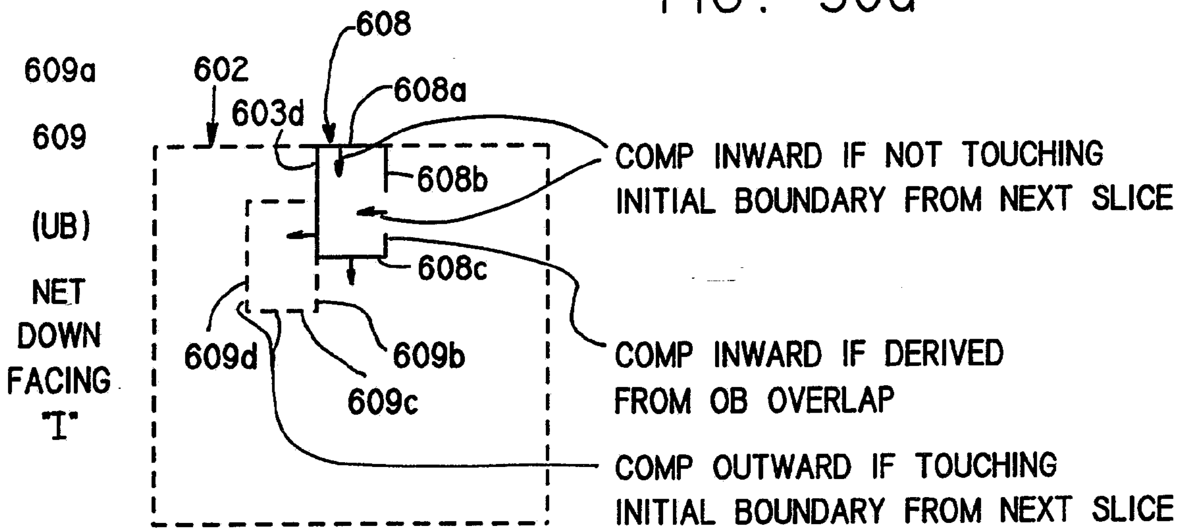

FIG. 30e

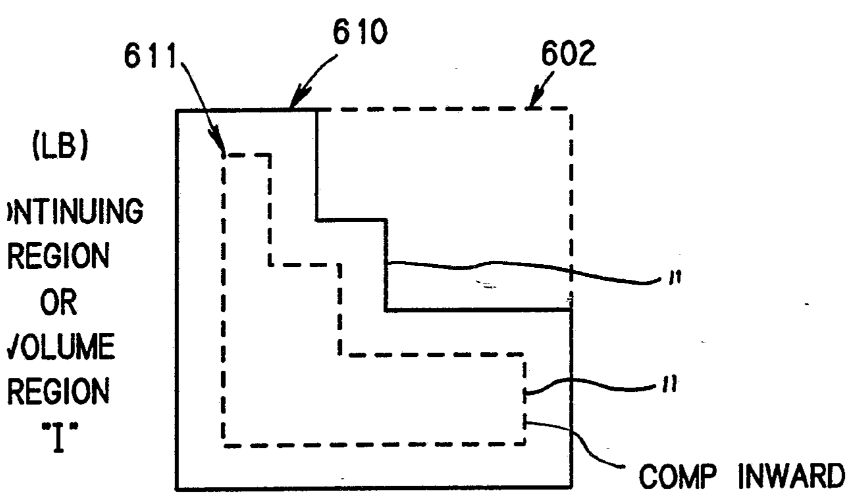

FIG. 30f

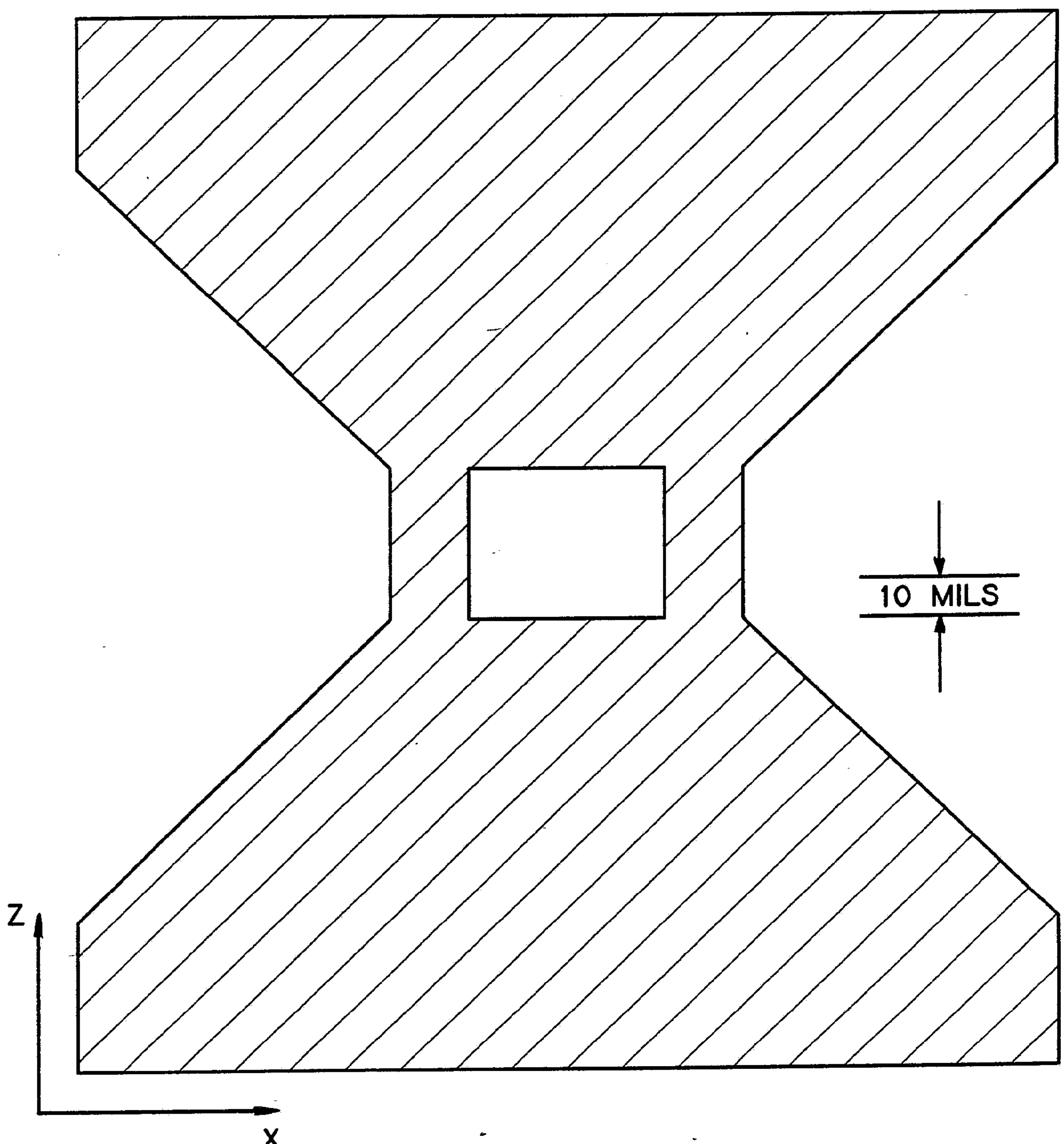

FIG. 31

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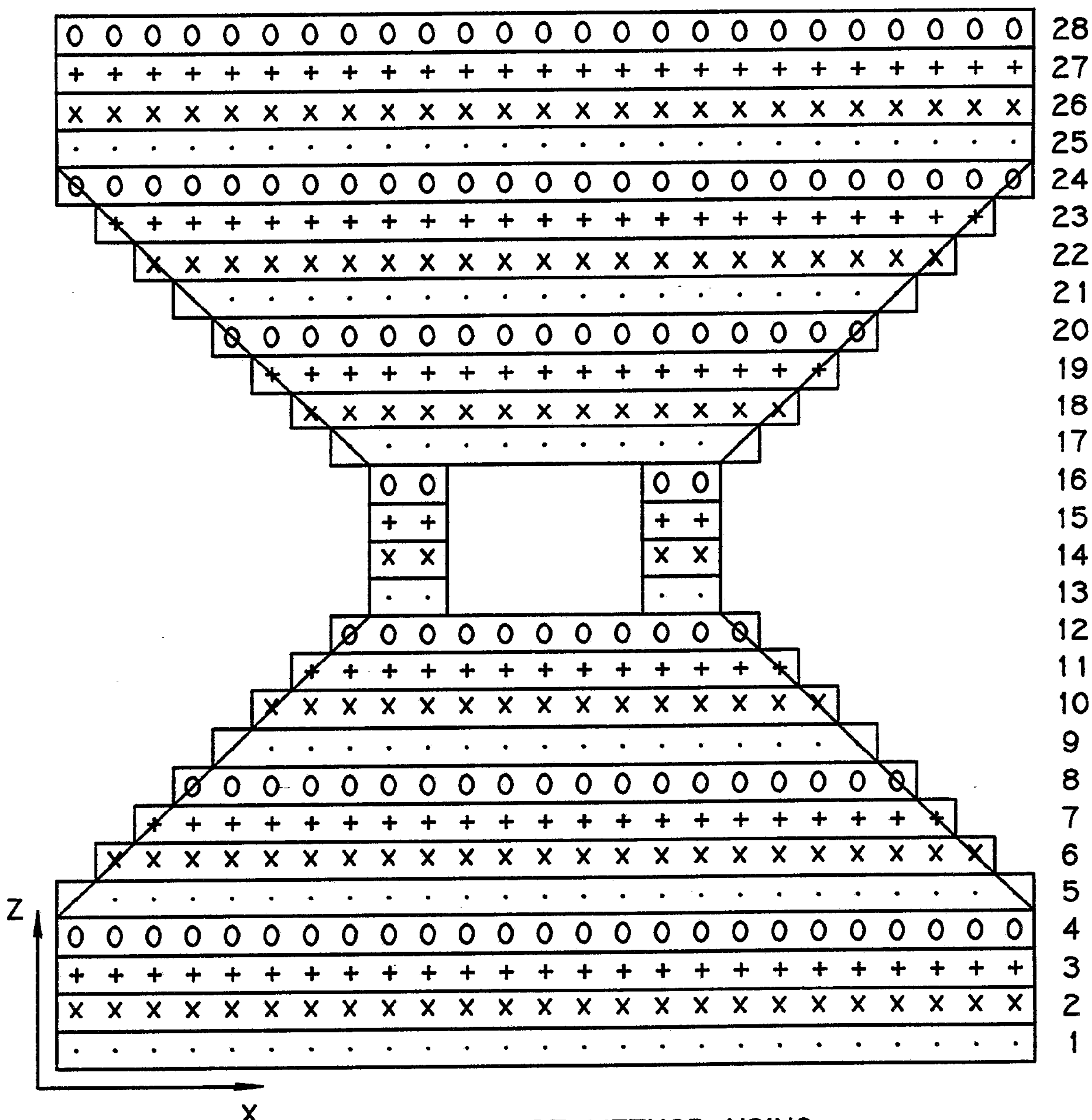

PRIOR ART METHOD USING
HIGH RESOLUTION MATERIAL

FIG. 32

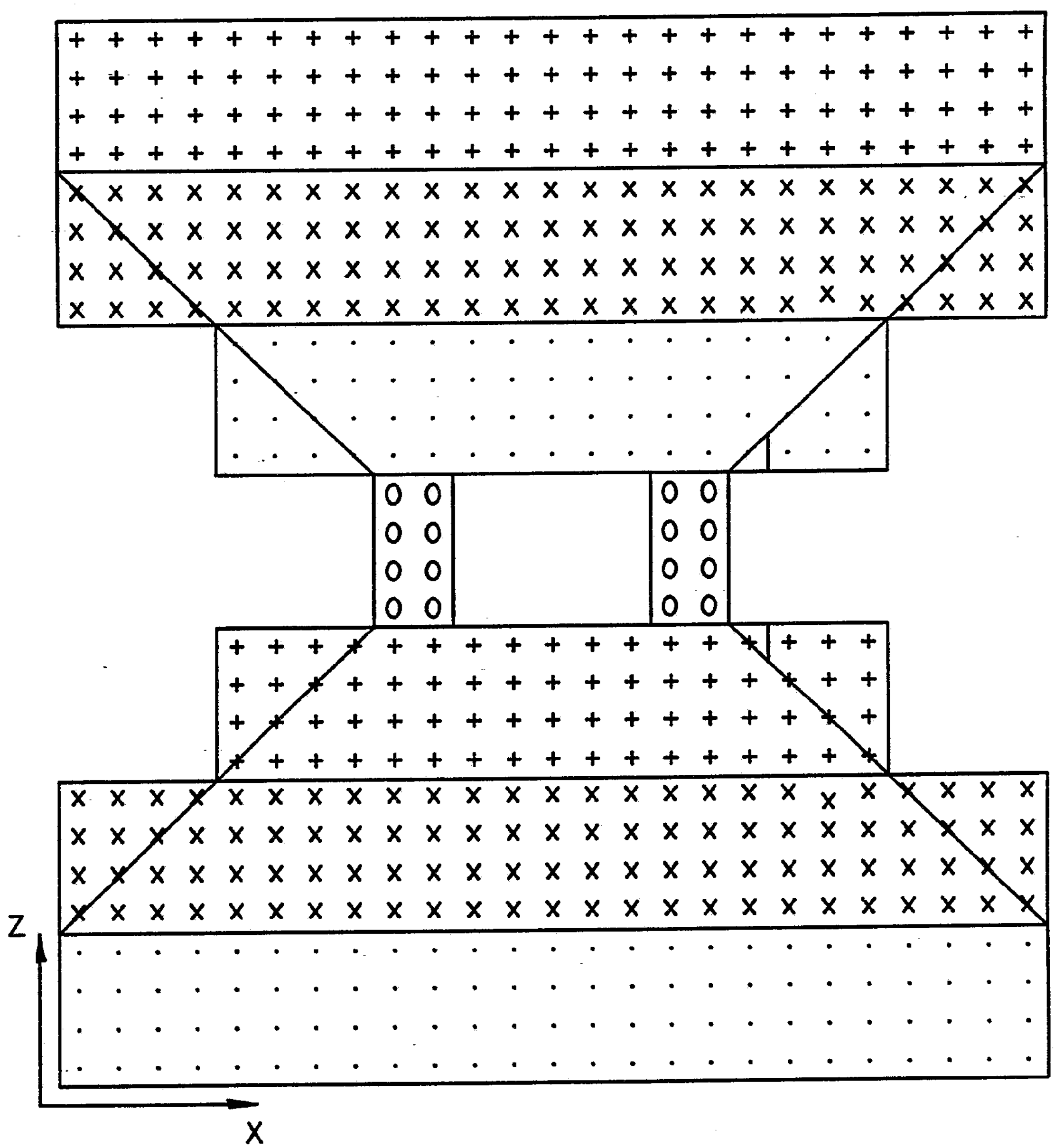

FIG. 33

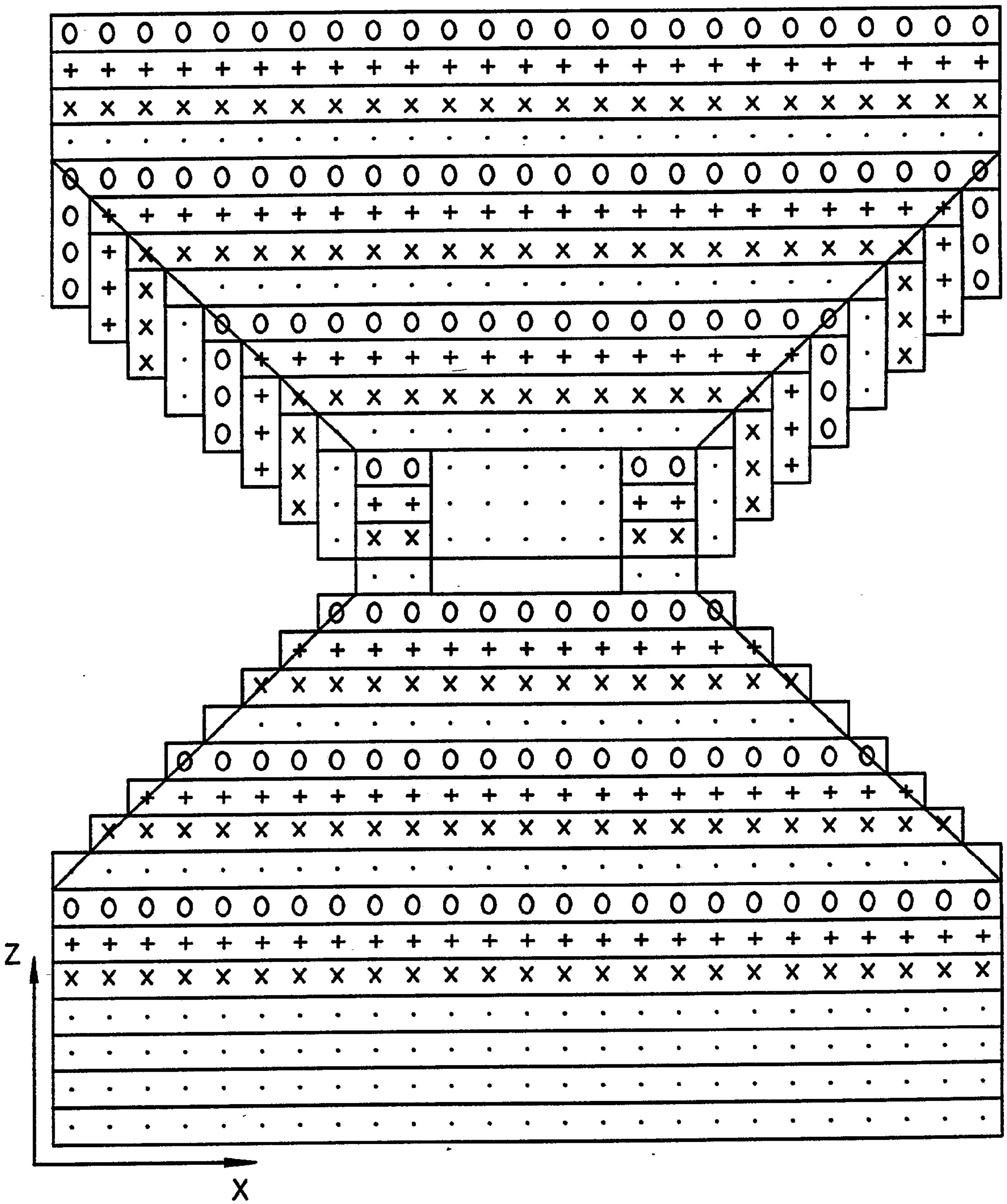

FIG. 34

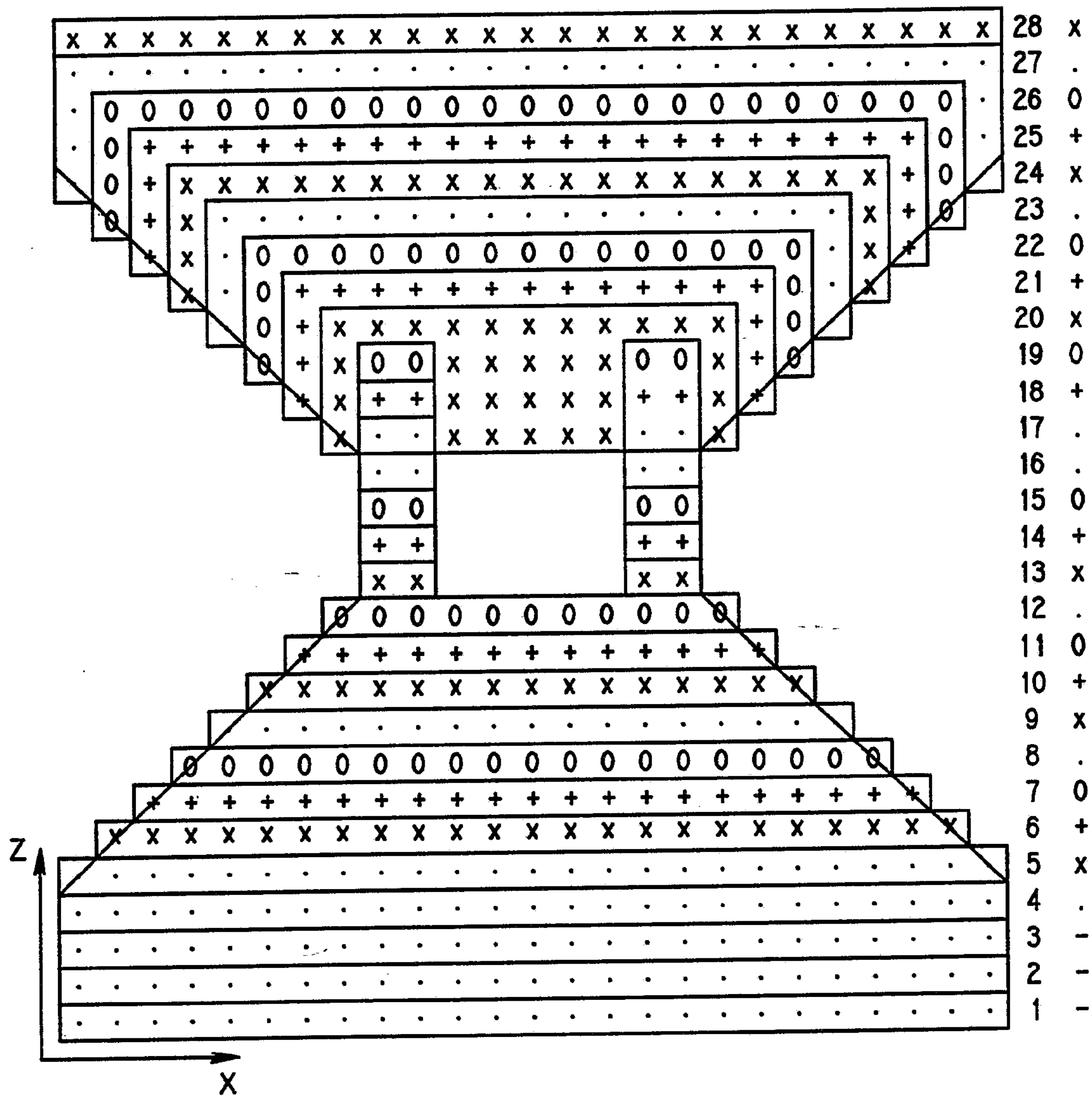

FIG. 35

– INDICATES NO CURING OCCURS

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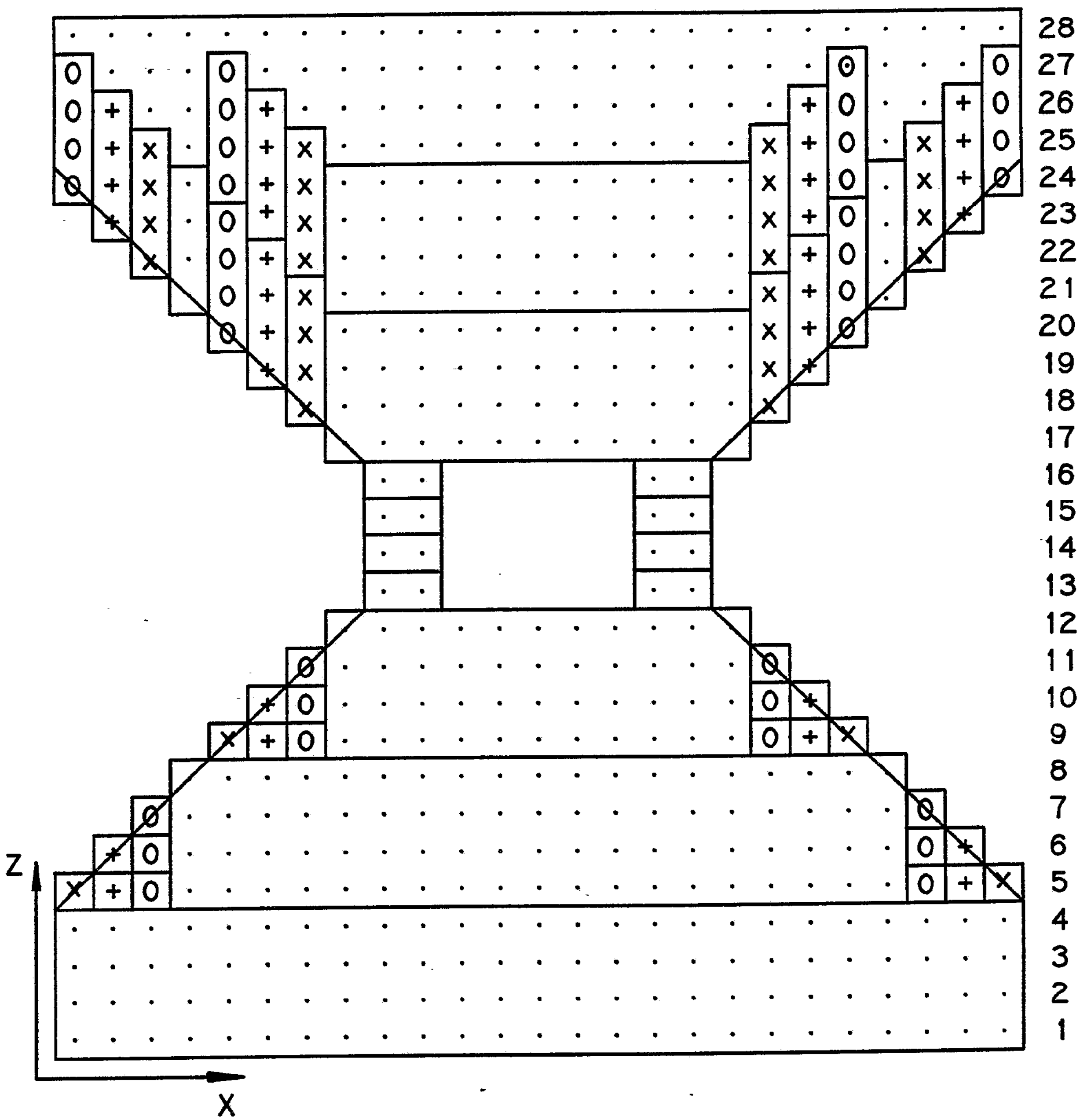

FIG. 36

LAYER INVOLVED IN THE CREATION OF THE OBJECT SHOWN IN FIGURE 2

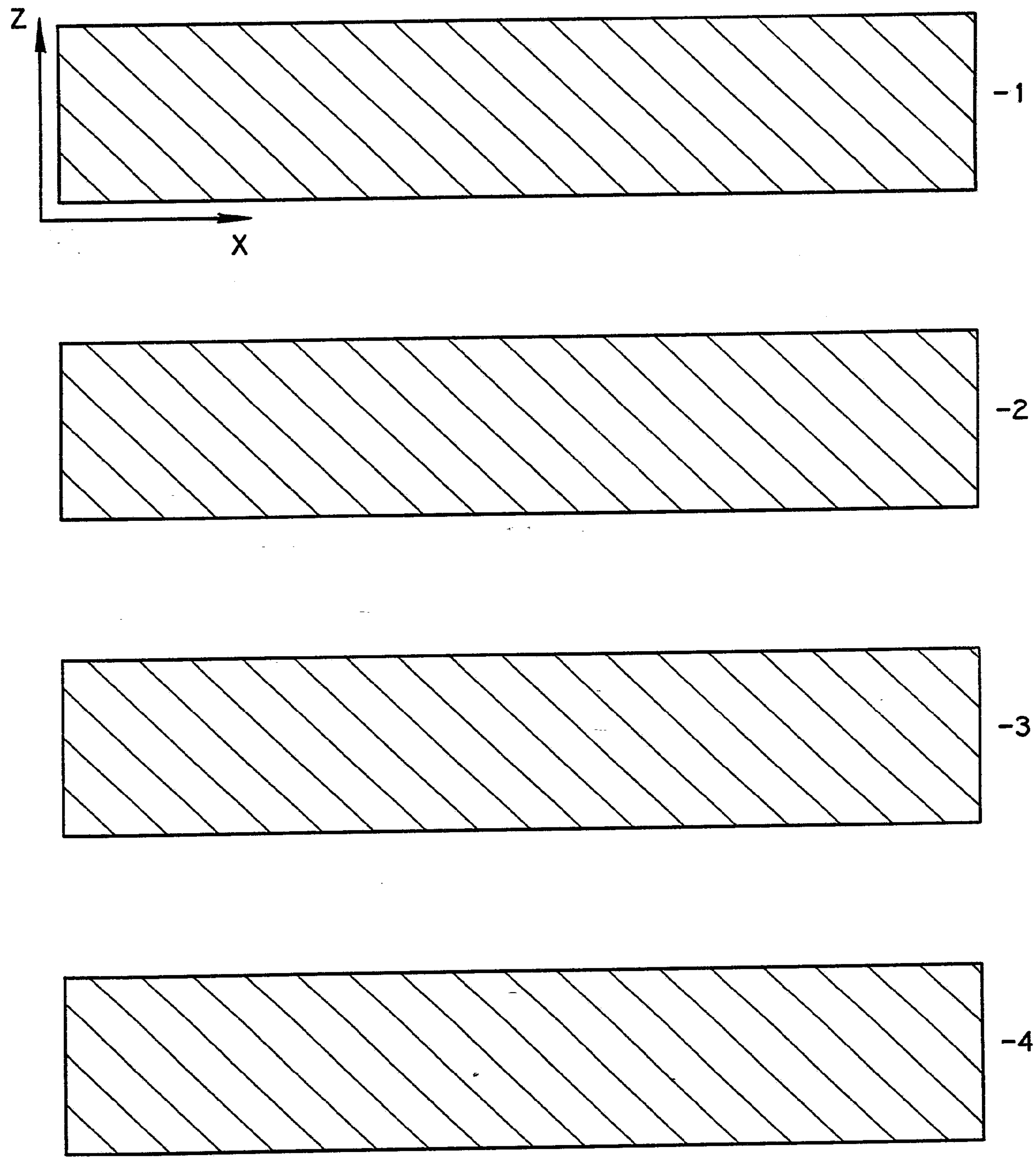

FIG. 37 1 of 7

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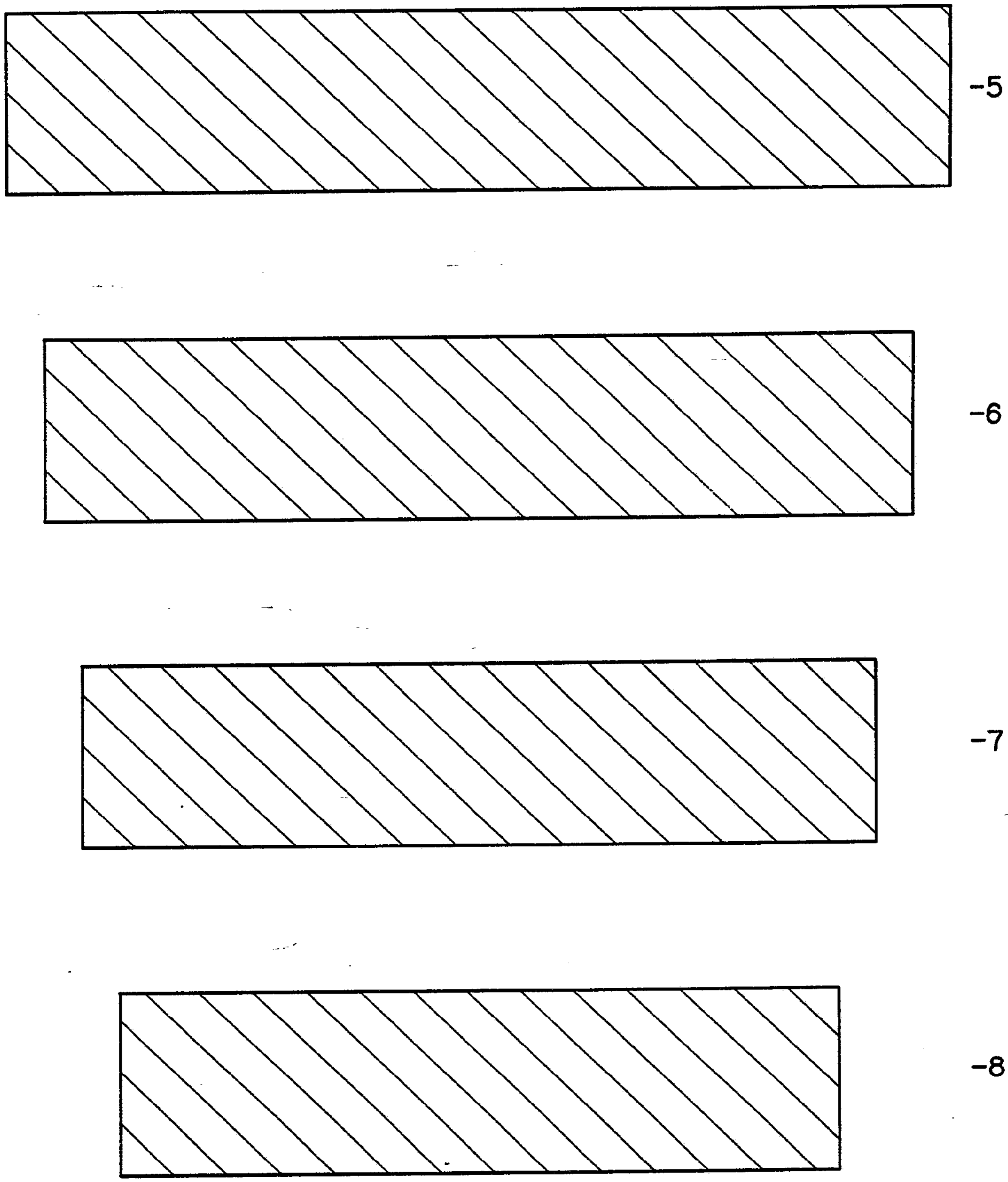

FIG. 37 2 of 7

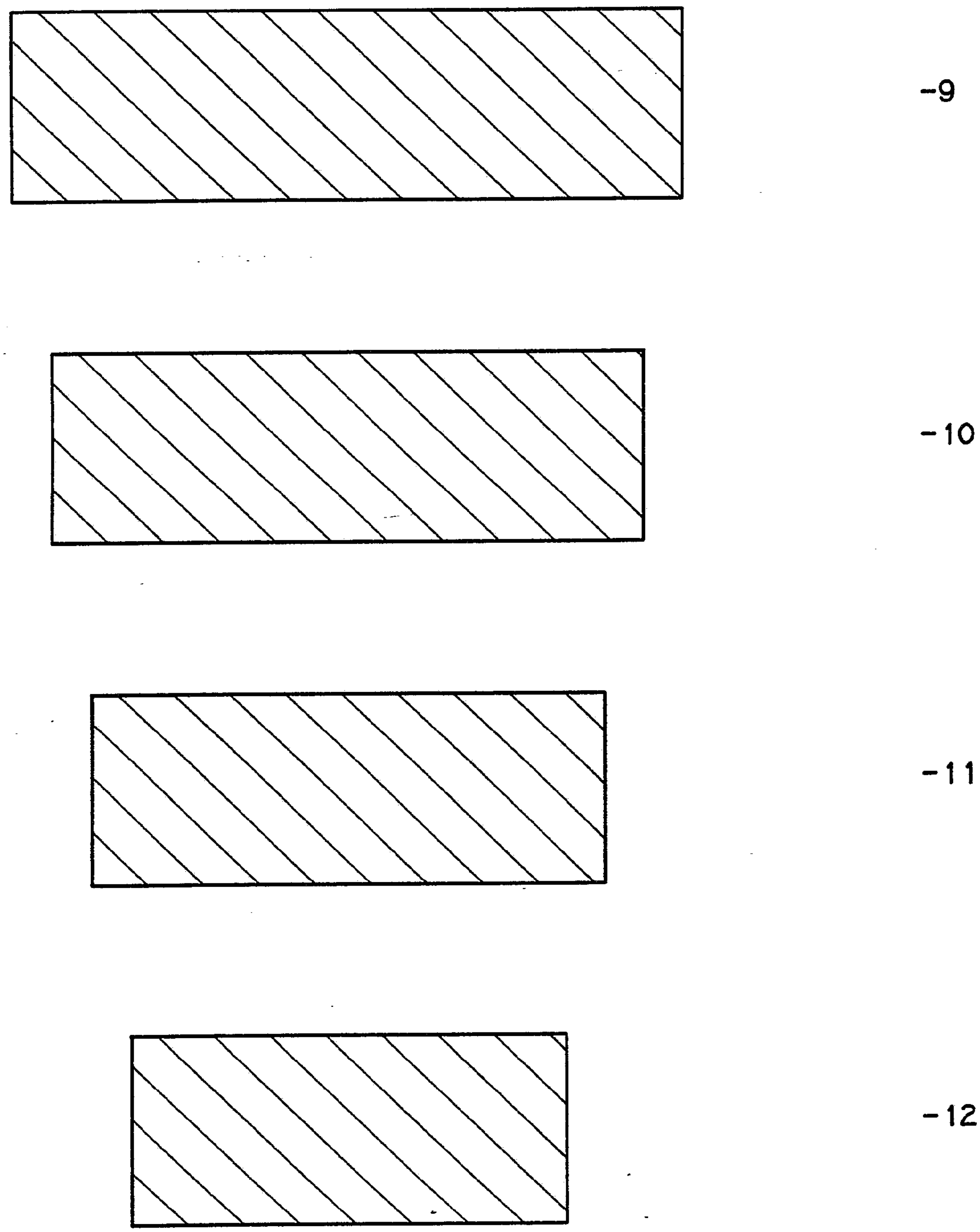

FIG. 37 3 of 7

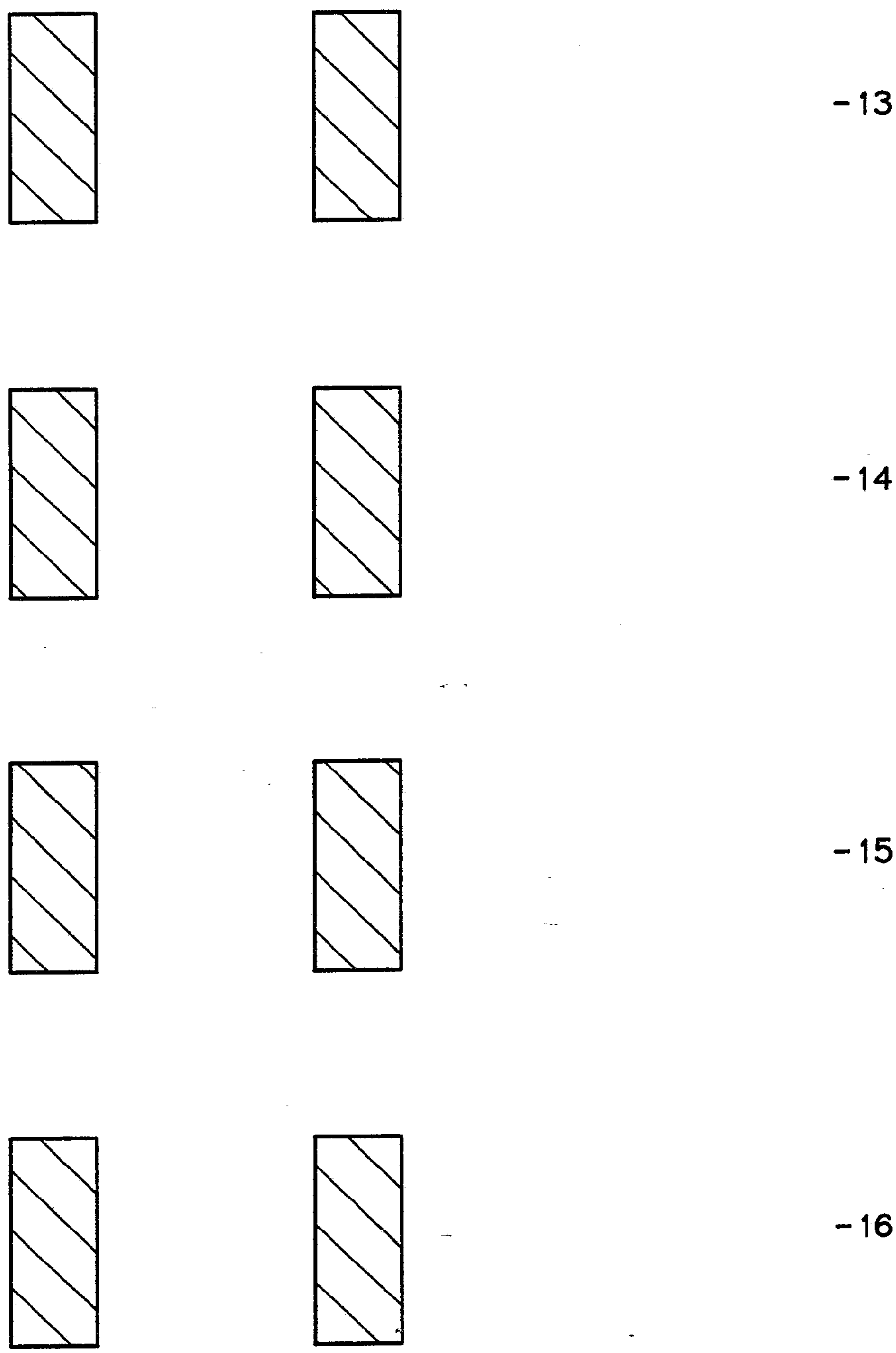

FIG. 37 4 of 7

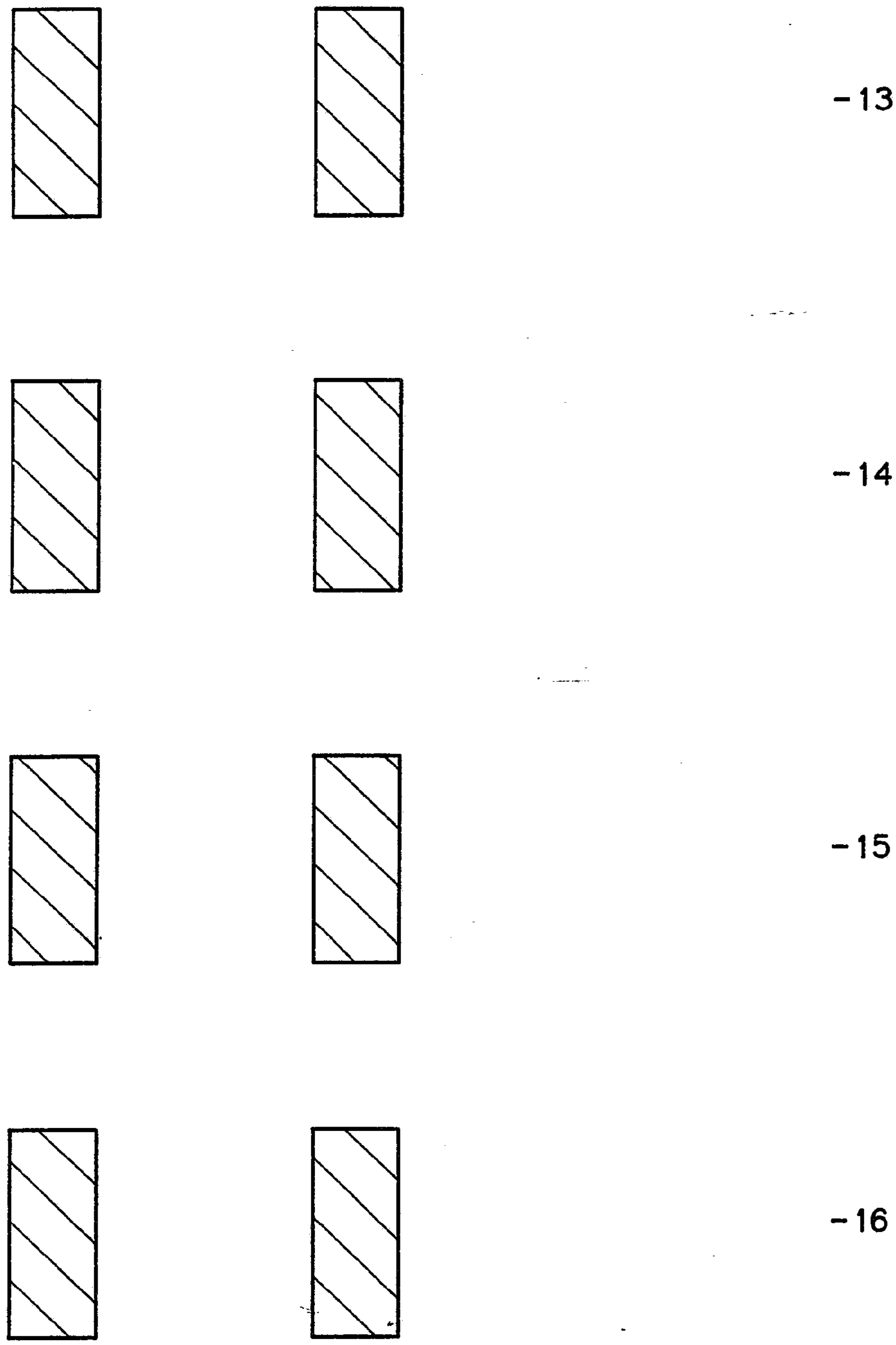

FIG. 37 4 of 7

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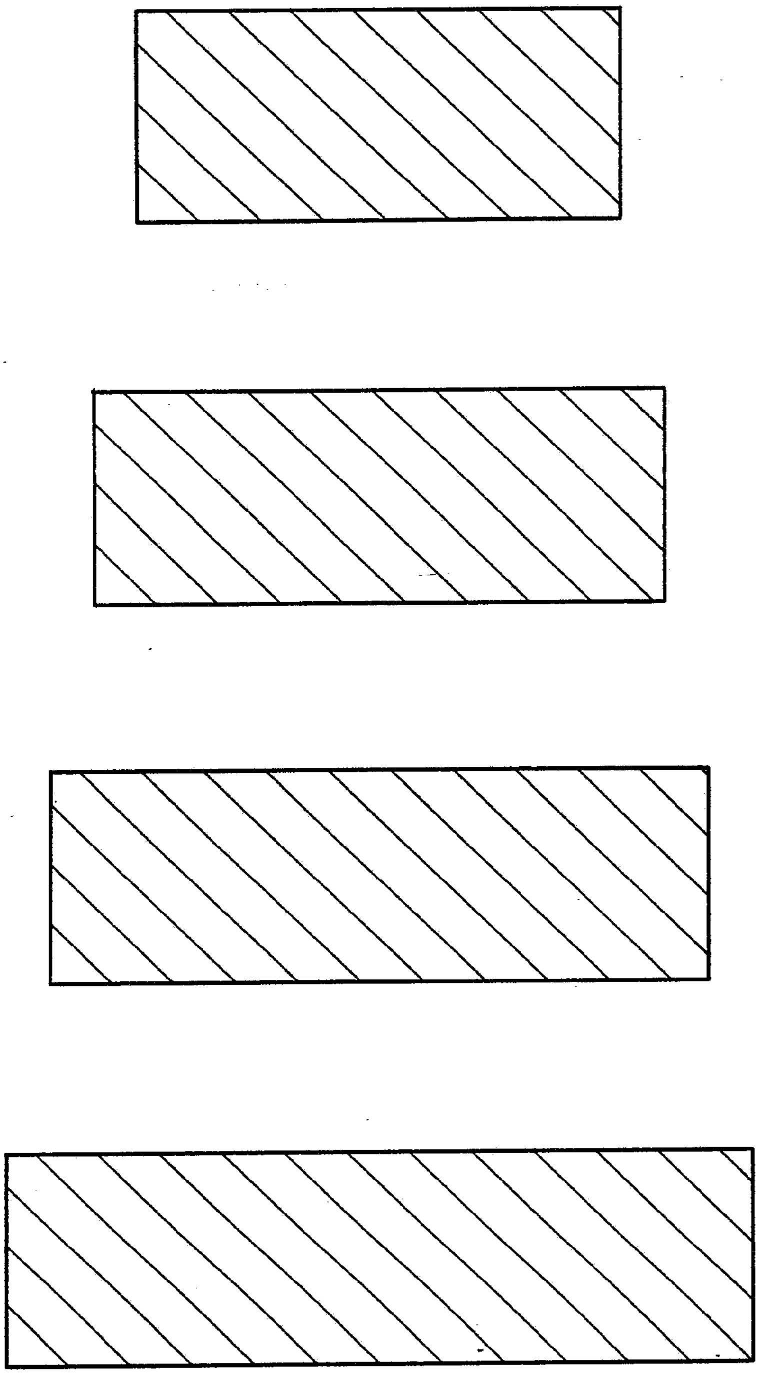

-17

-18

-19

-20

FIG. 37 5 of 7

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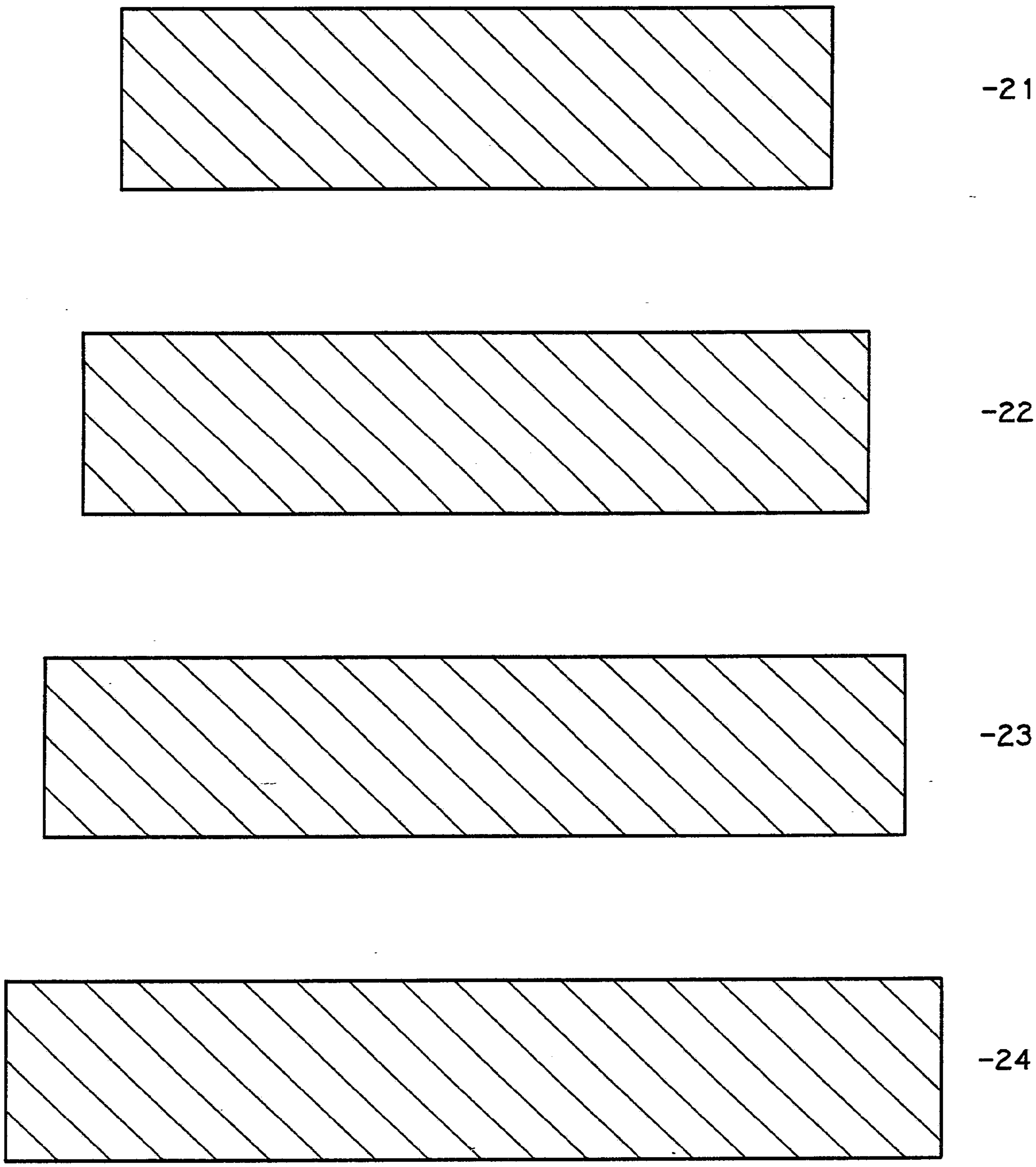

FIG. 37 6 of 7

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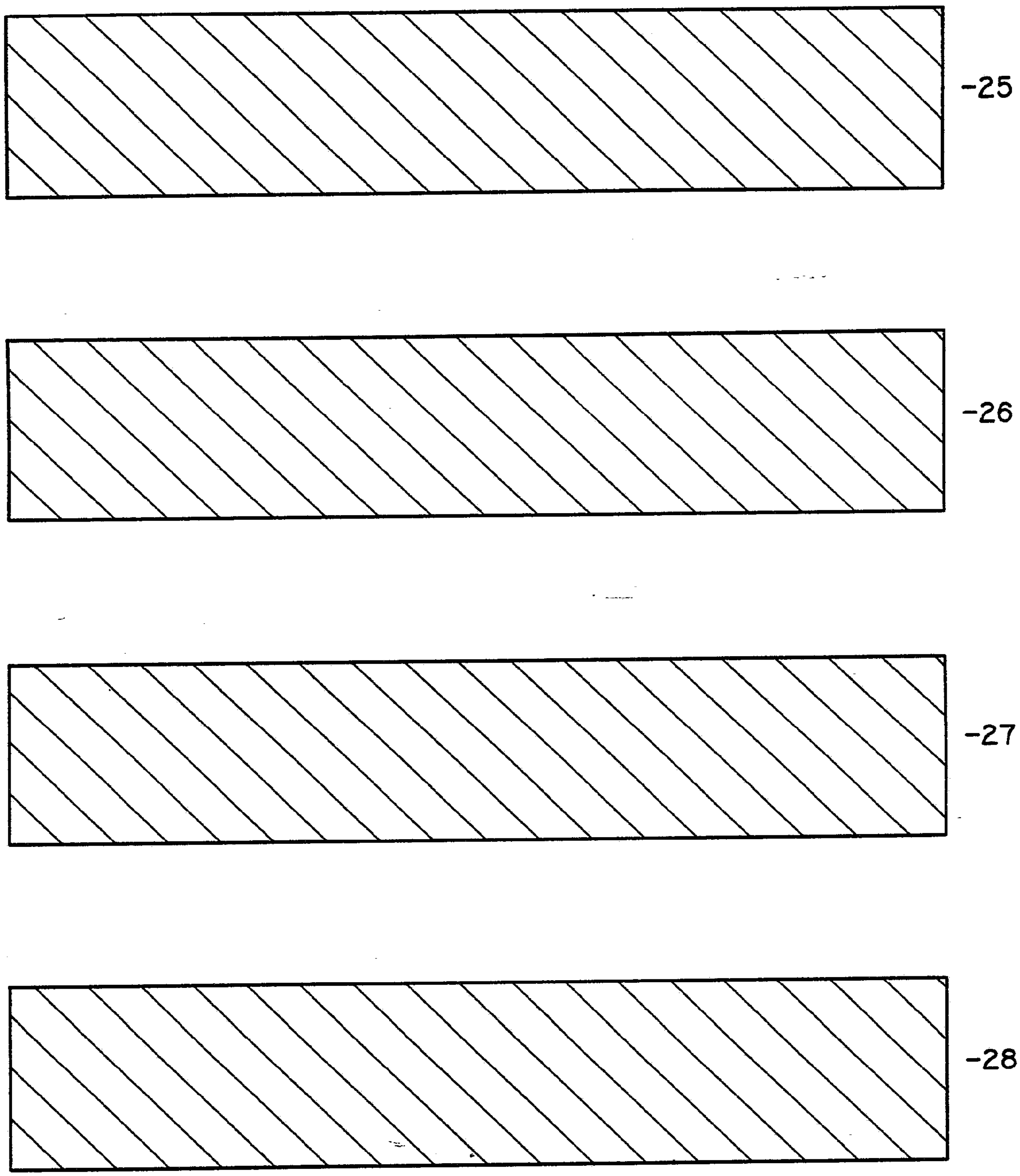
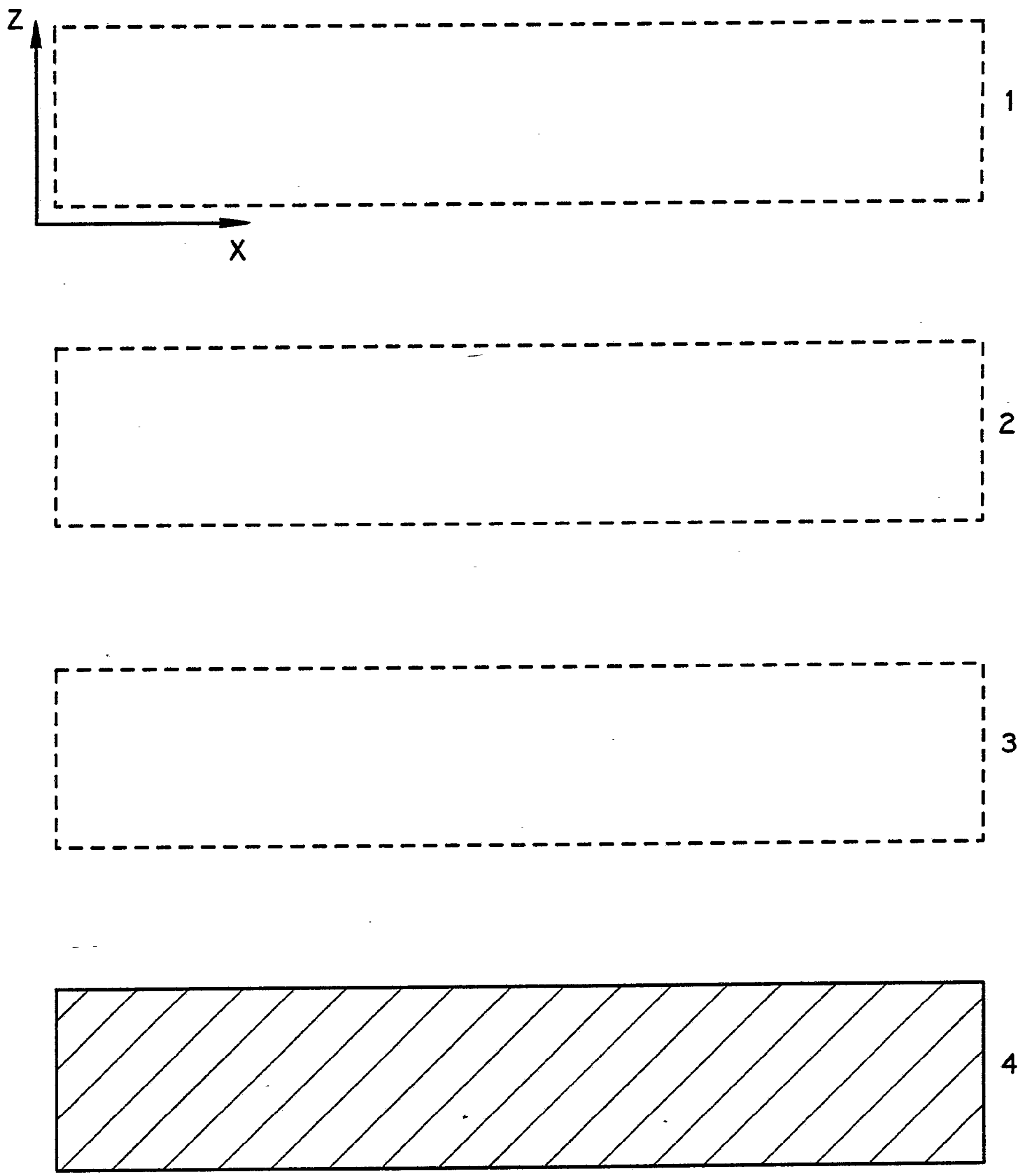


FIG. 37

LATERS INVOLVED IN THE CREATION OF THE OBJECT SHOWN IN FIGURE 5



= MSD CURE DEPTH

= NOT NECESSARILY MSD CURE DEPTH

FIG. 38 1 of 7

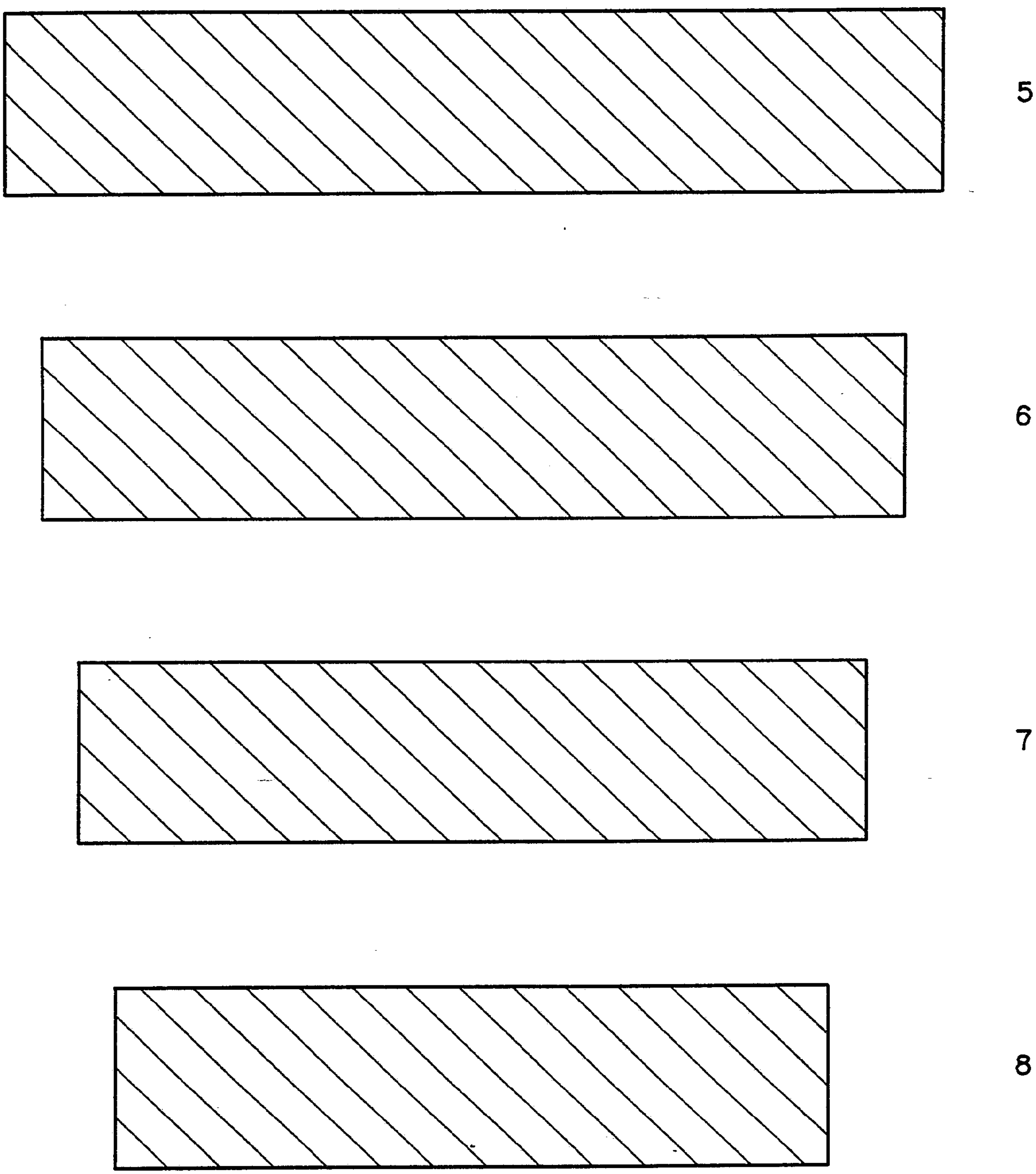


FIG. 38 2 of 7

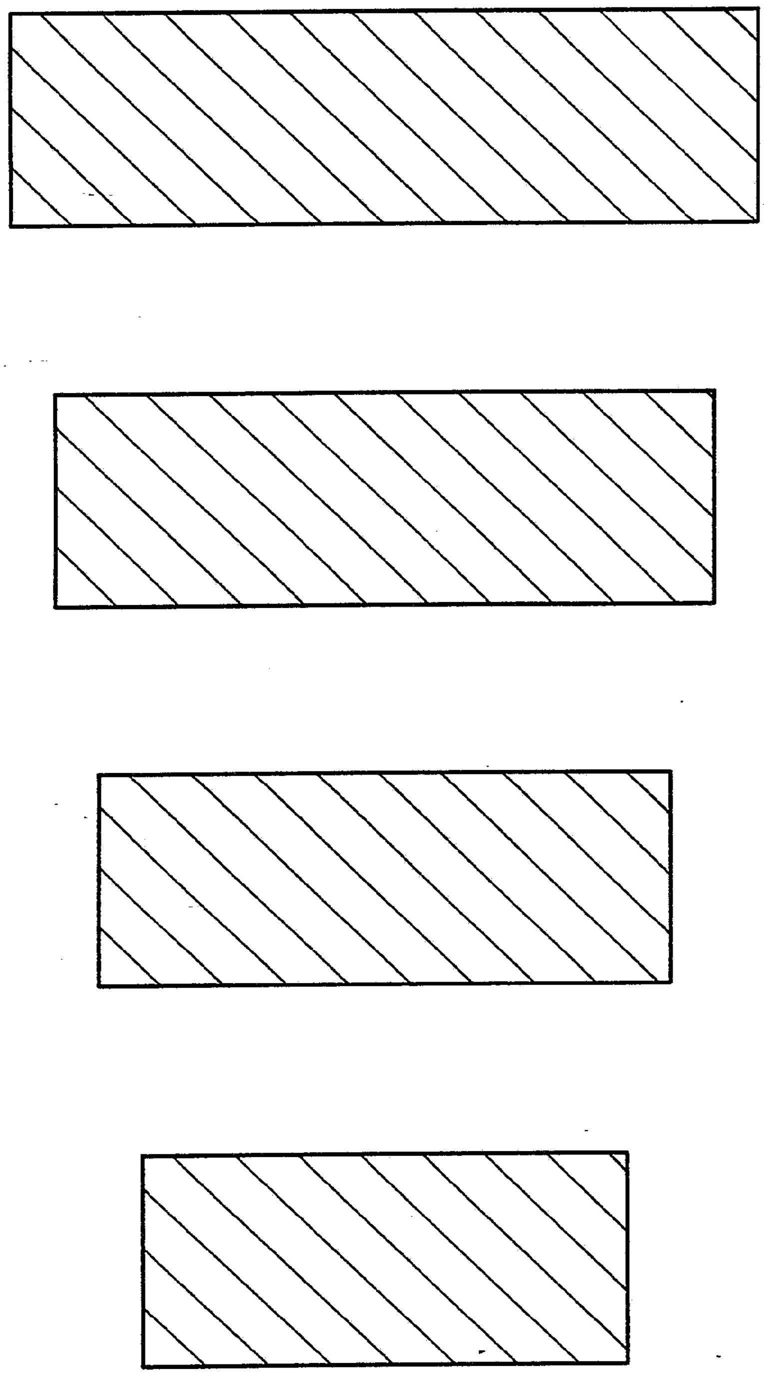


FIG. 38 3 of 7

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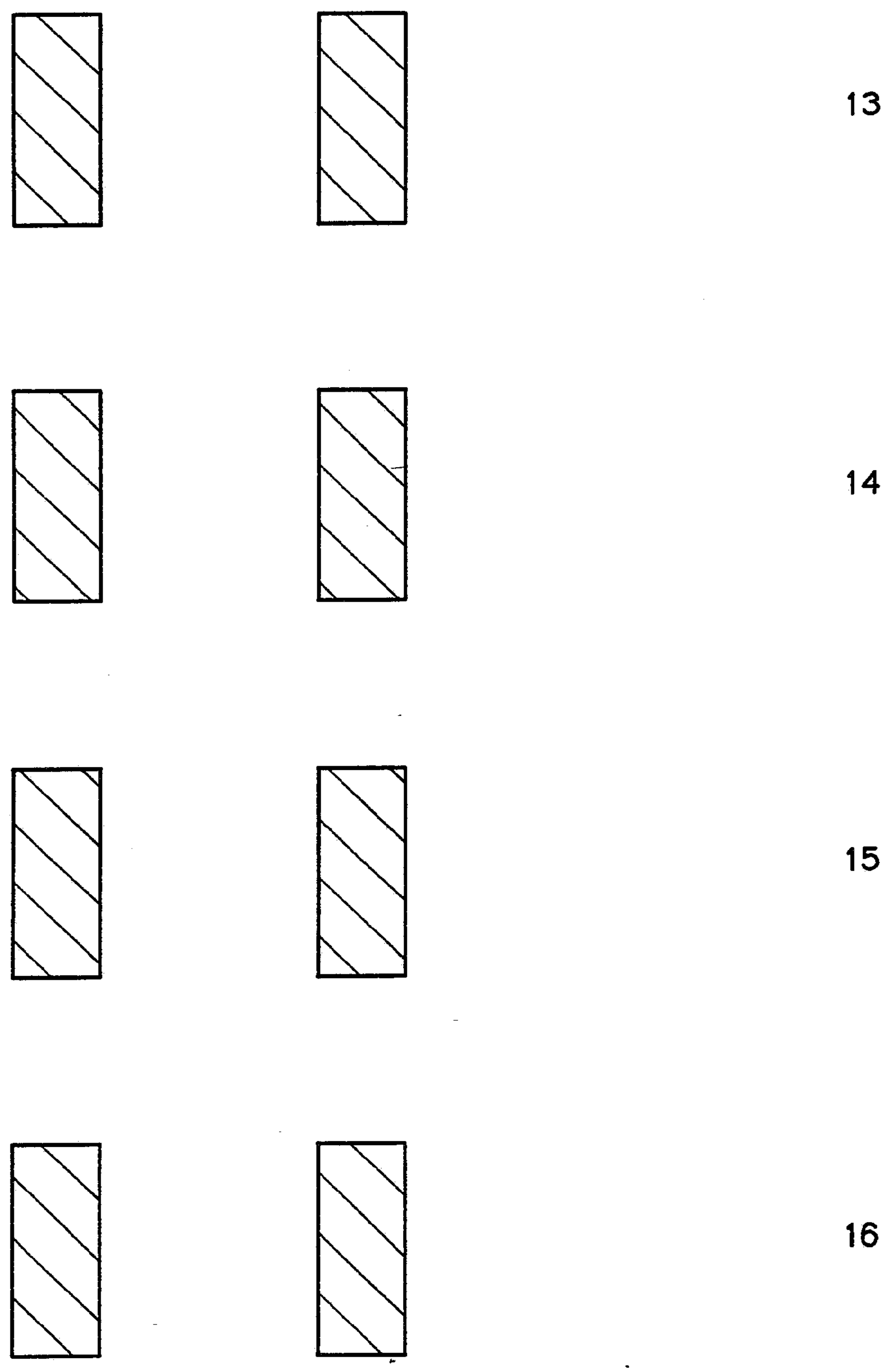

FIG. 38 4 of 7

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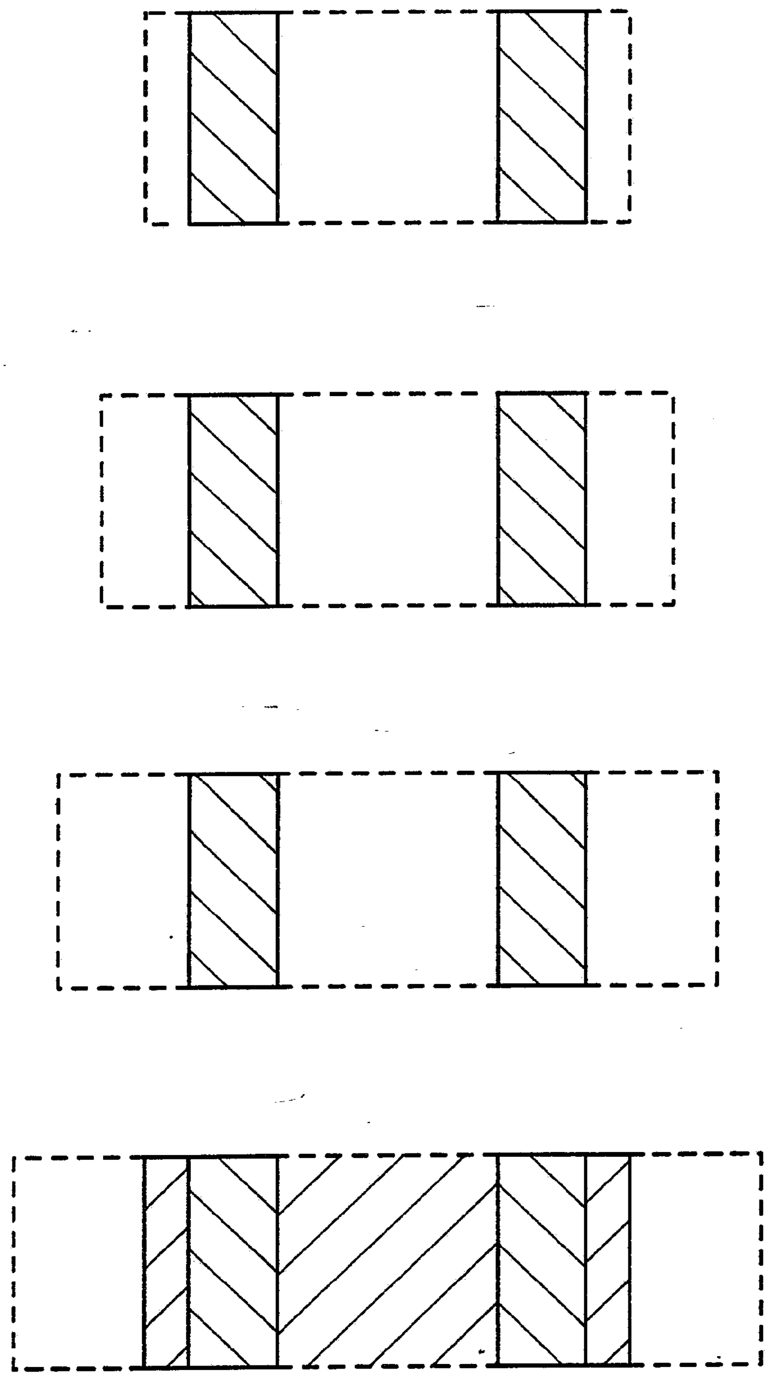

17

18

19

20

FIG. 38 5 of 7

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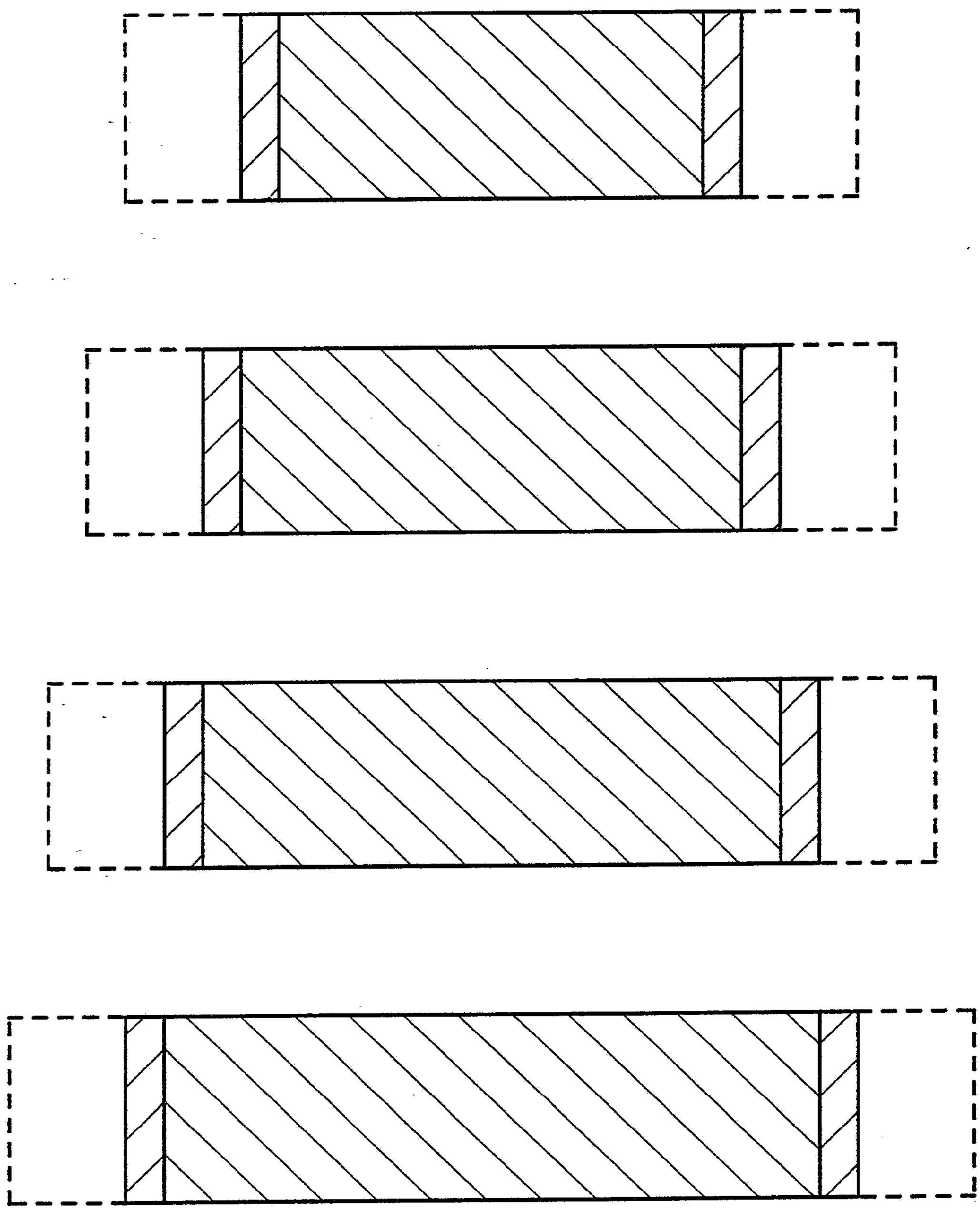

FIG. 38

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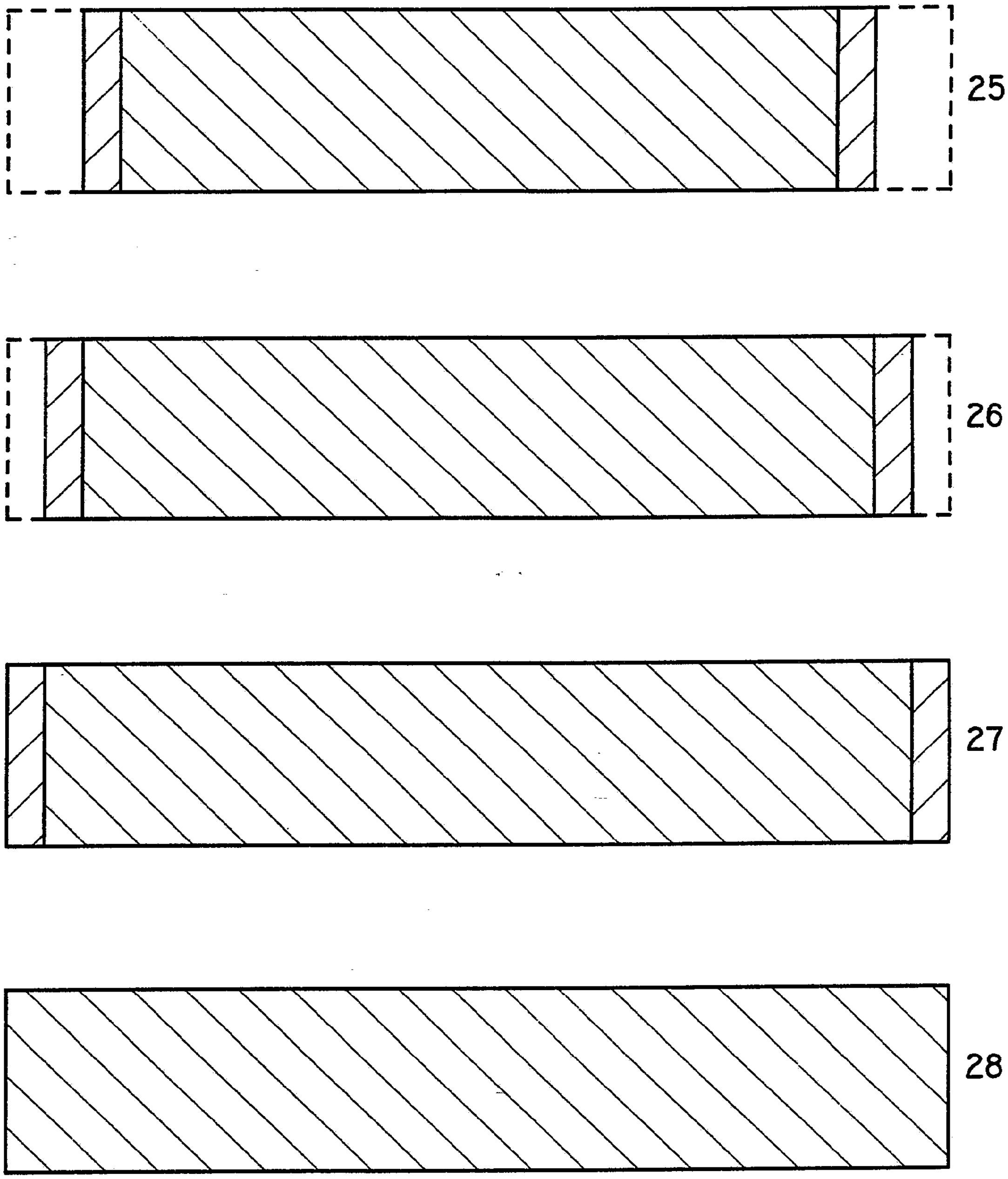

FIG. 38 7 of 7

LATERS INVOLVED IN THE CREATION OF THE OBJECT SHOWN IN FIGURE 6

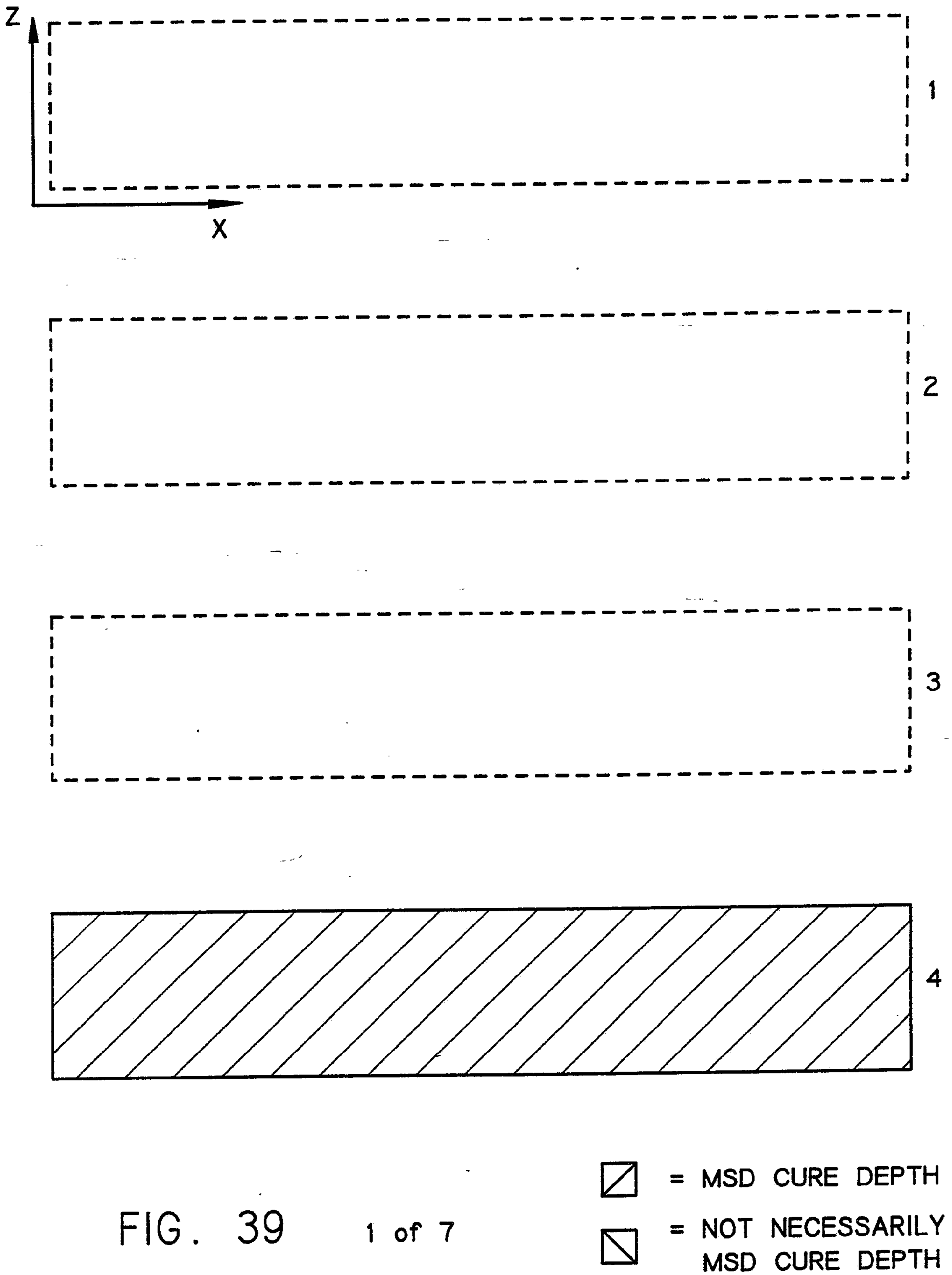

FIG. 39 1 of 7

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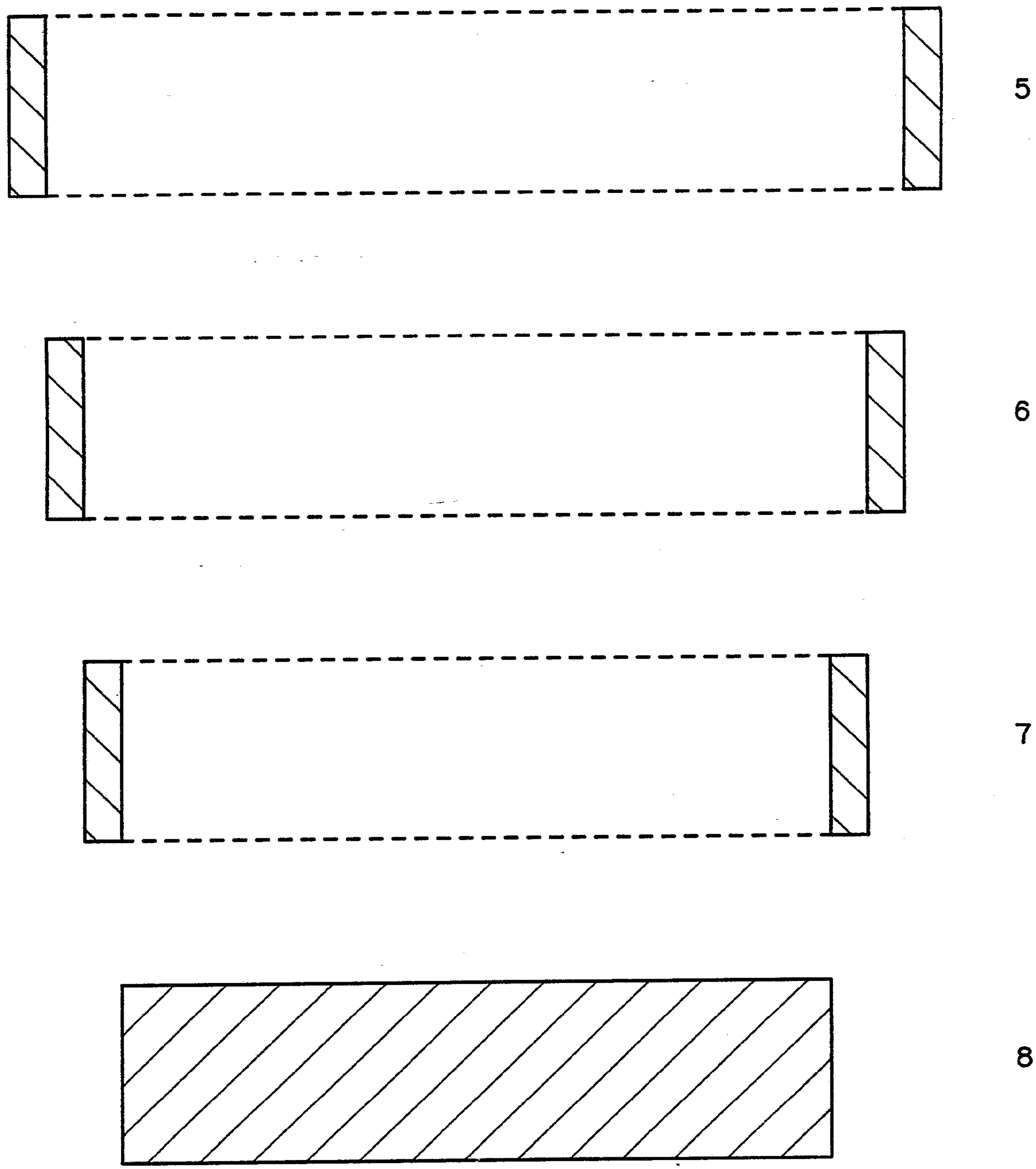

FIG. 39 2 OF 7

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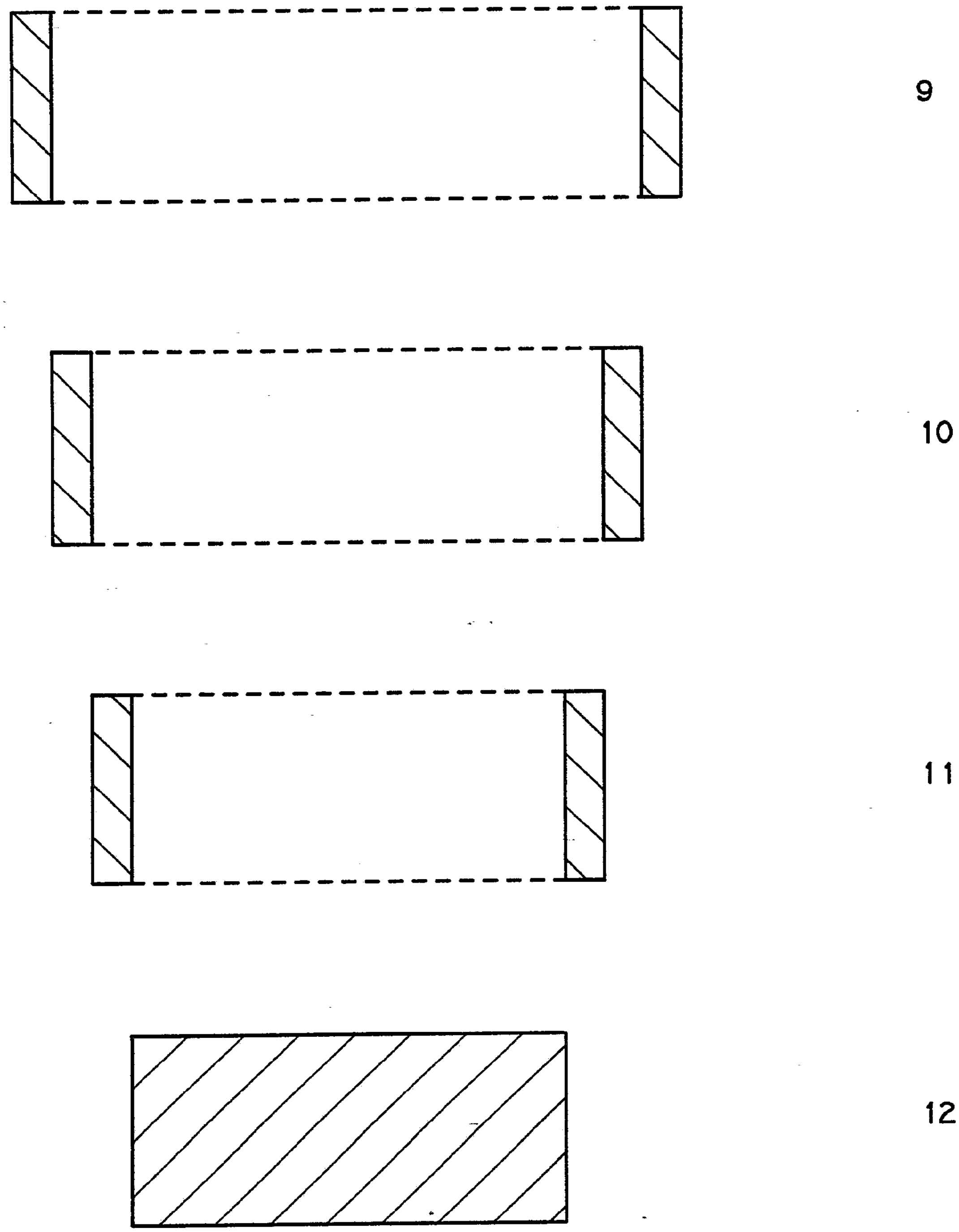

FIG. 39 3 of 7

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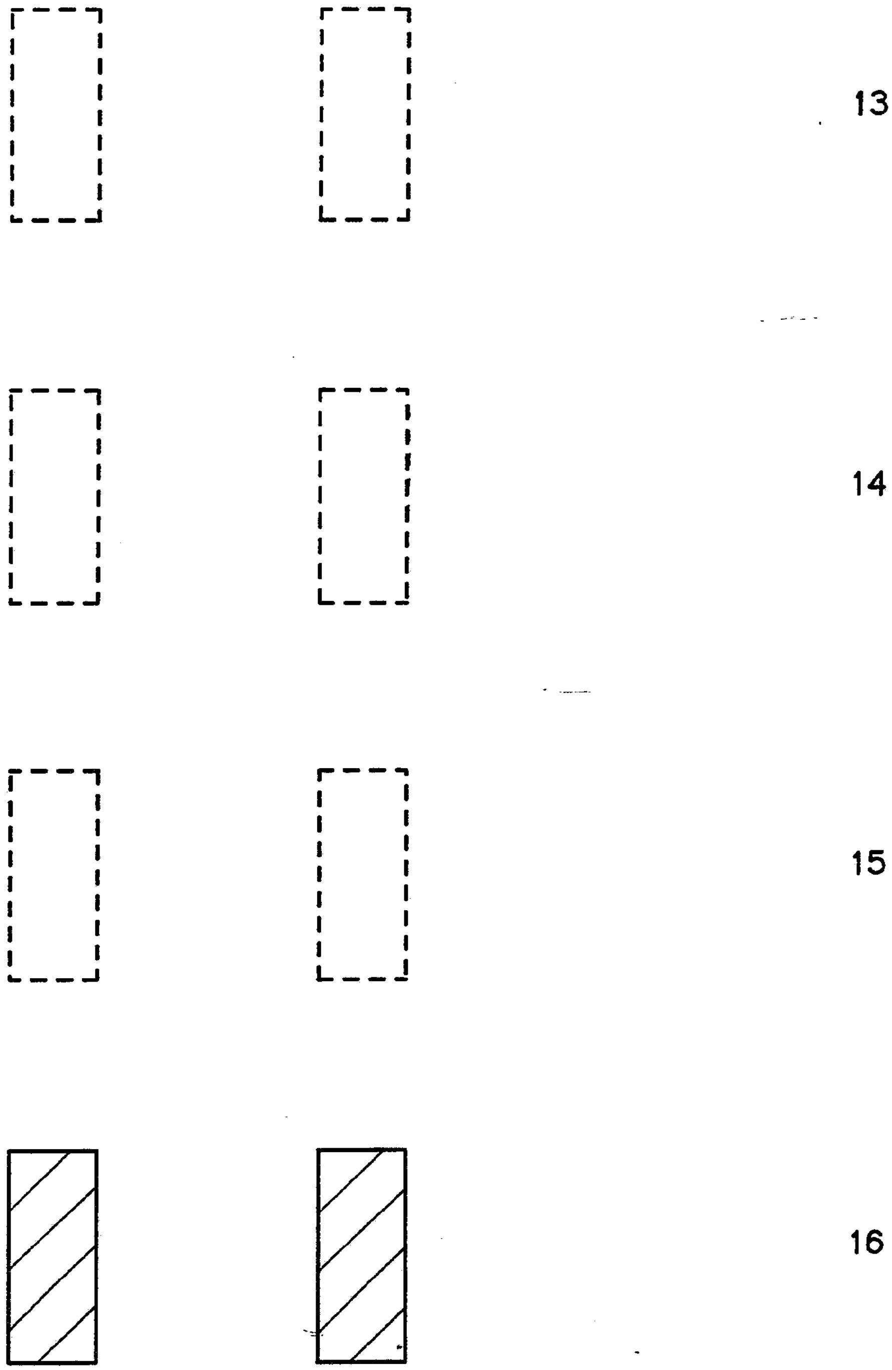

FIG. 39 4 of 7

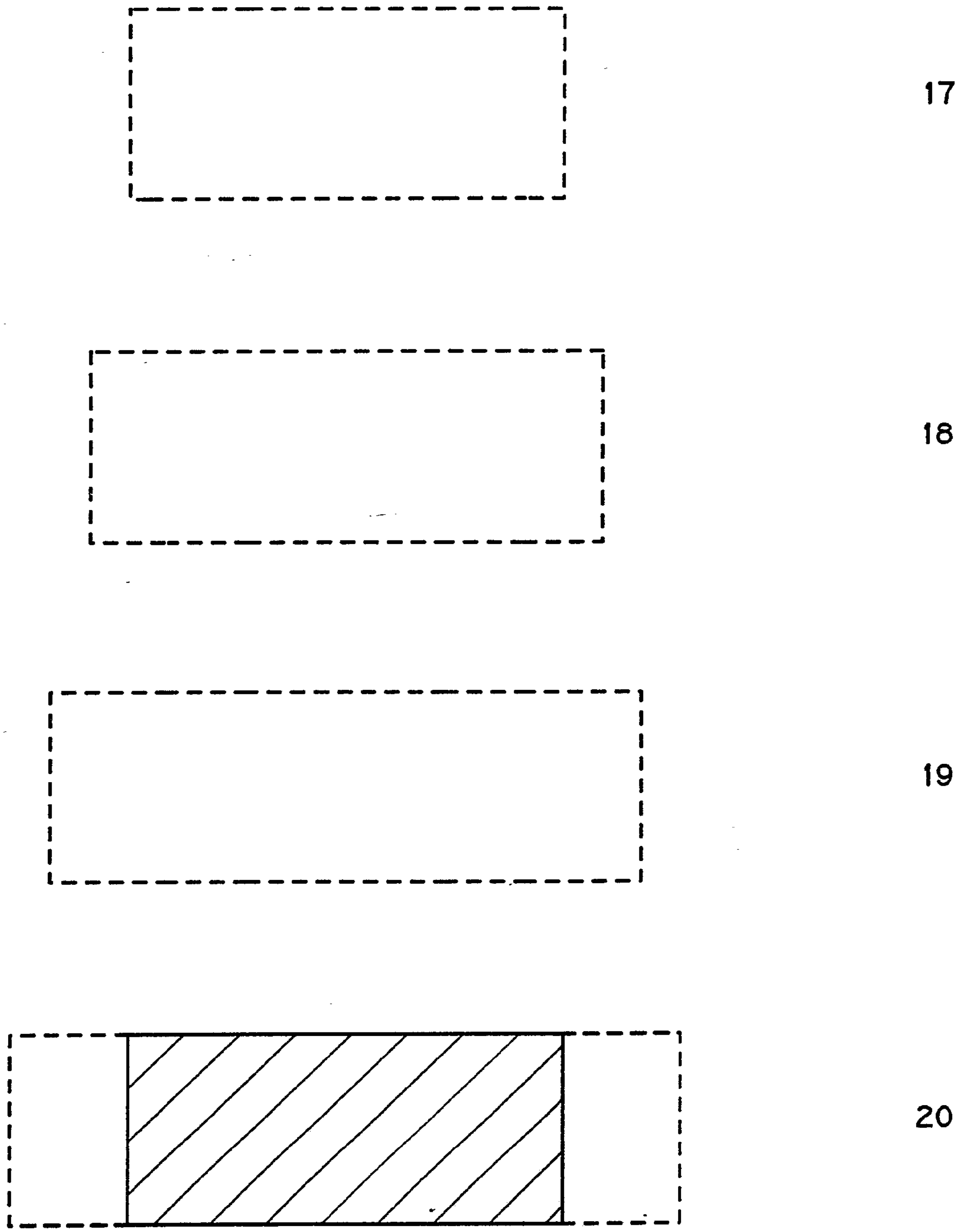

FIG. 39 5 of 7

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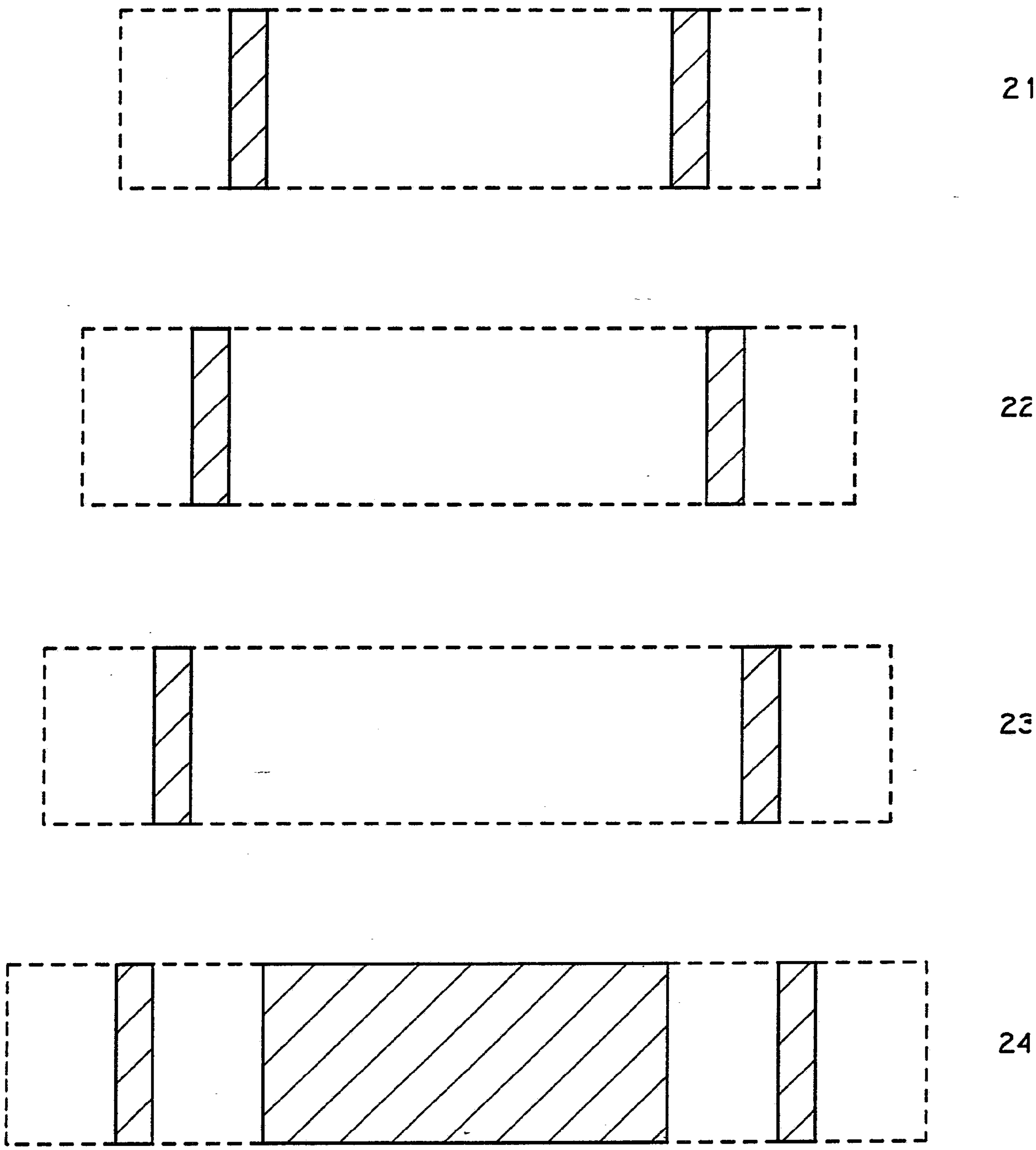

FIG. 39 6 of 7

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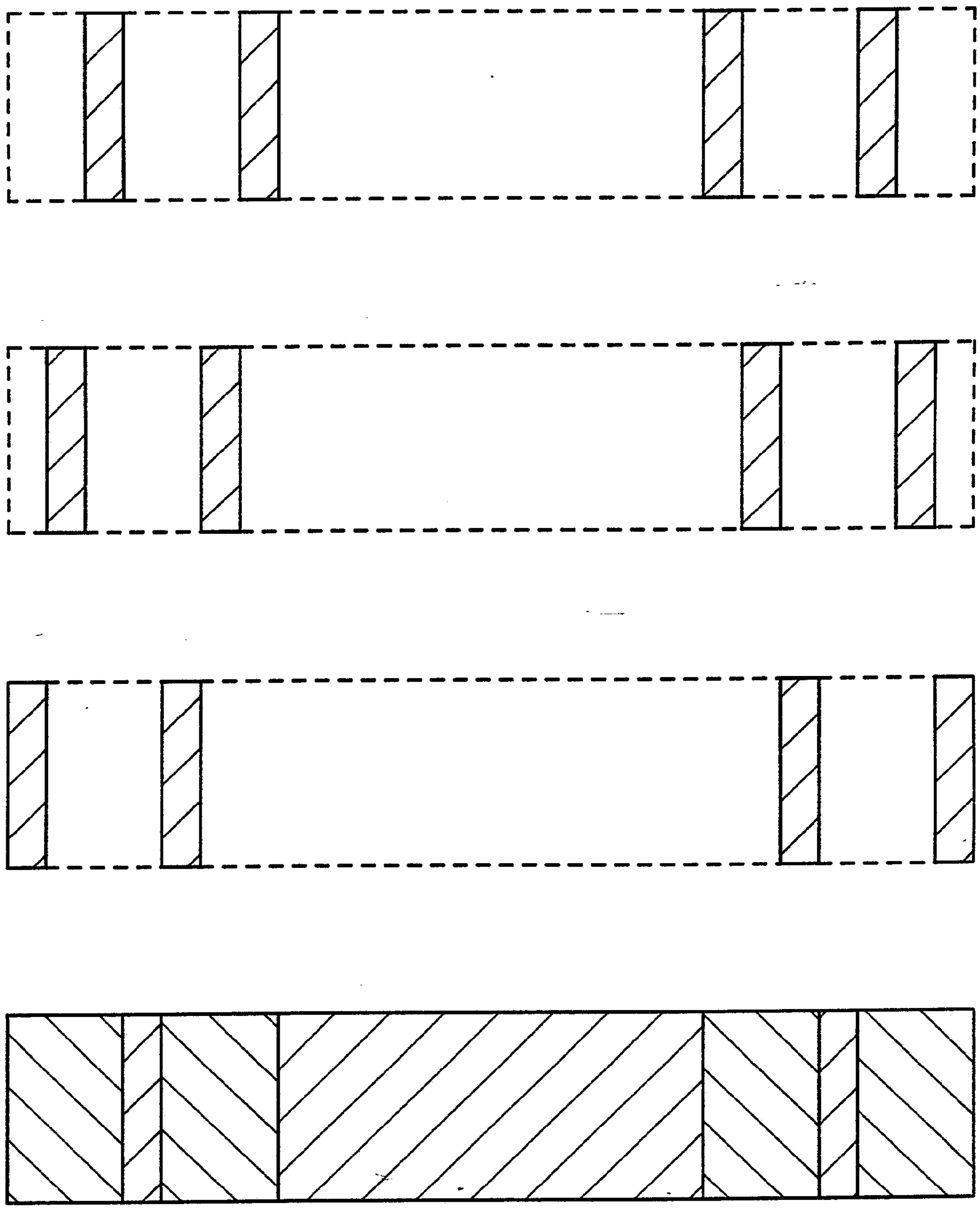


FIG. 39

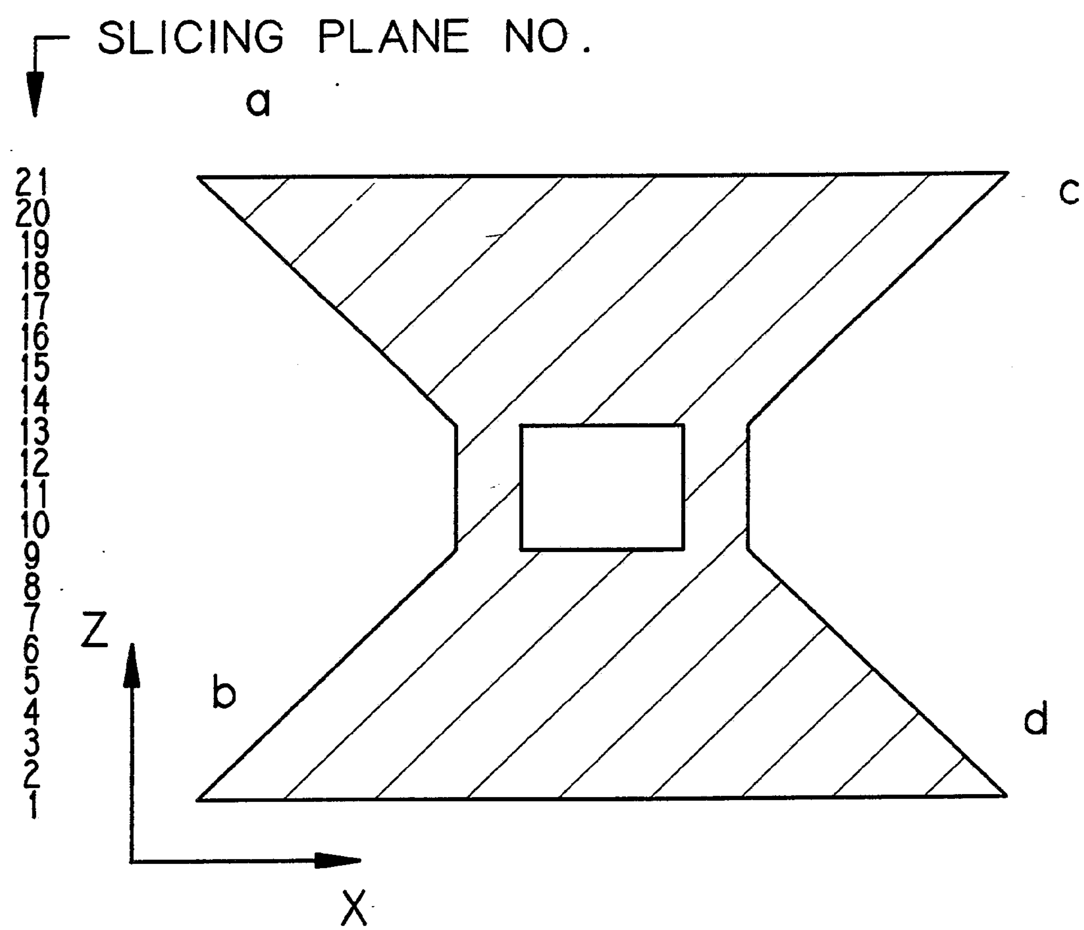
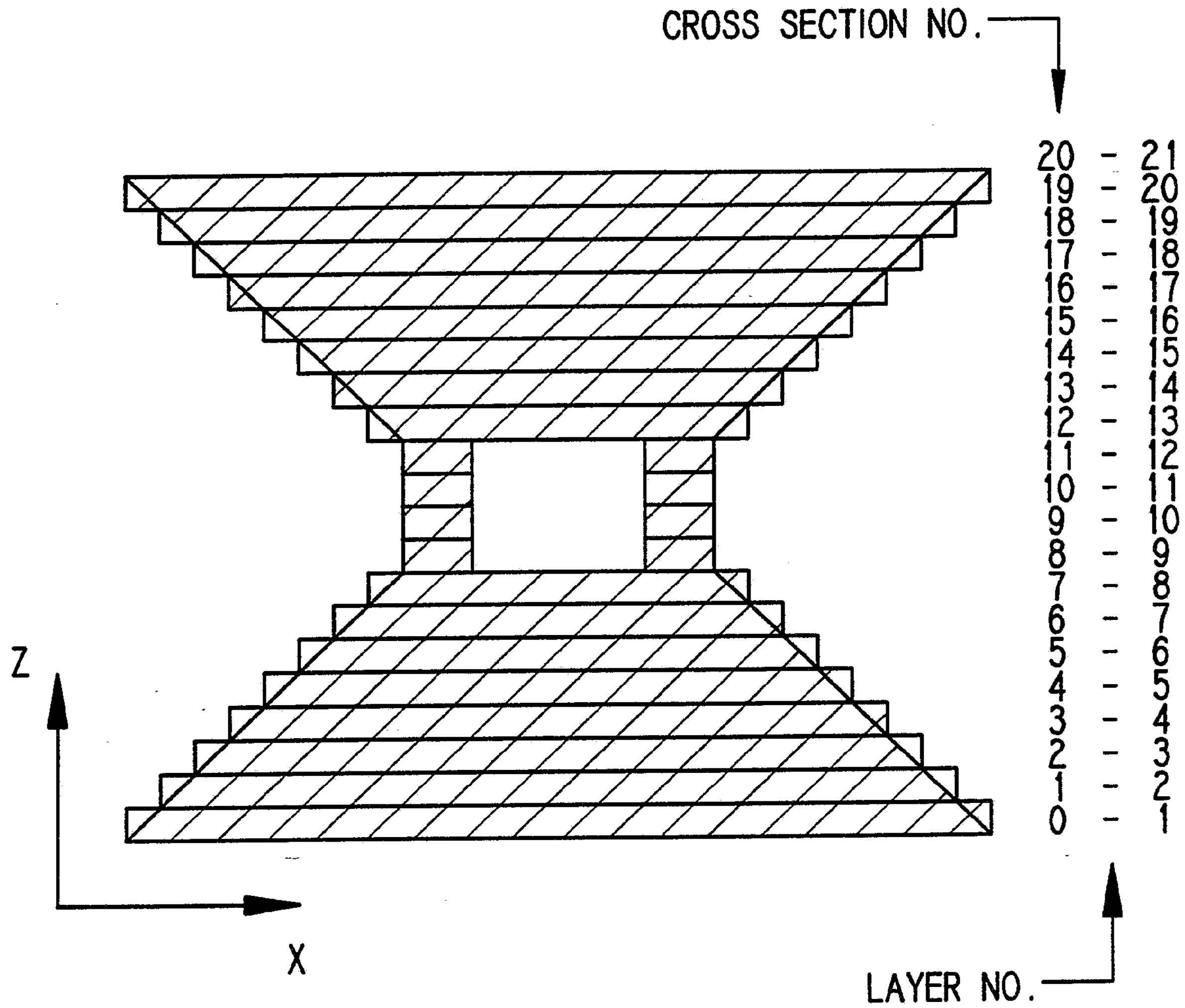

SLICING PLANE NO.
a
c
b
d
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
Z
X

FIG. 40



PRIOR ART METHOD USING
A HIGH RESOLUTION MATERIAL

FIG. 41

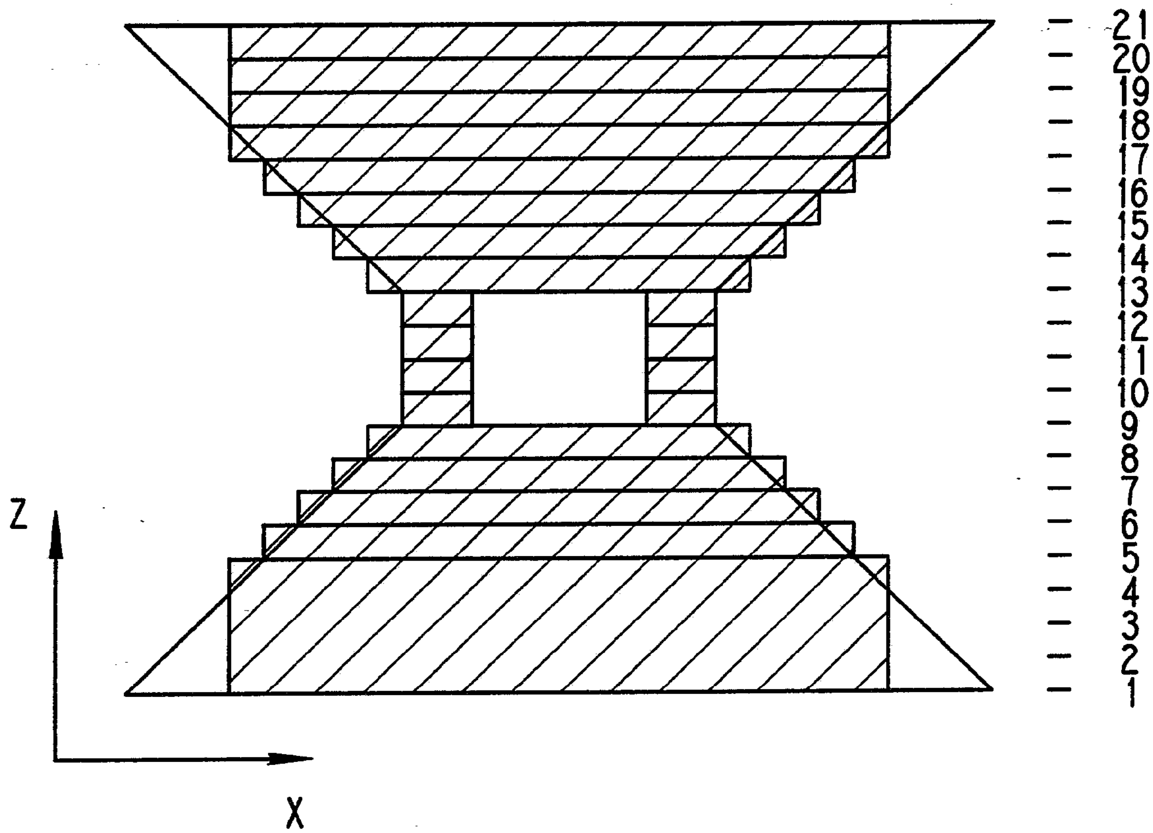


FIG. 42

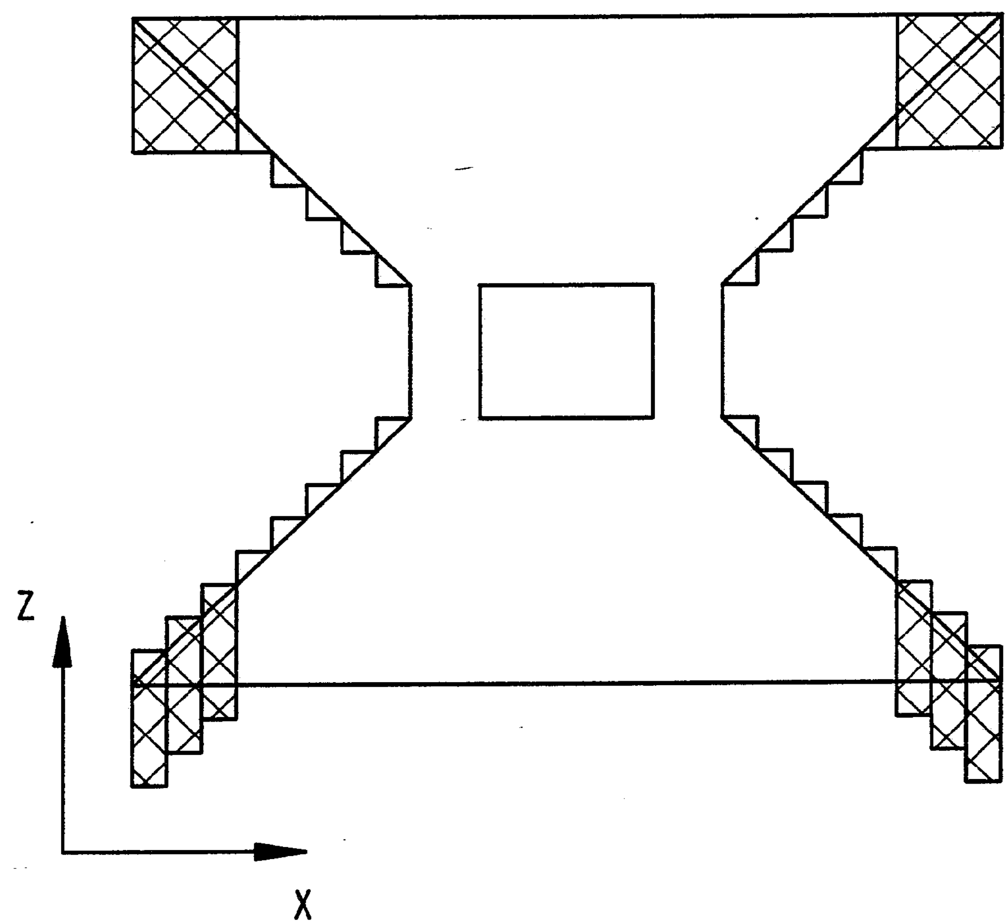


FIG. 43a

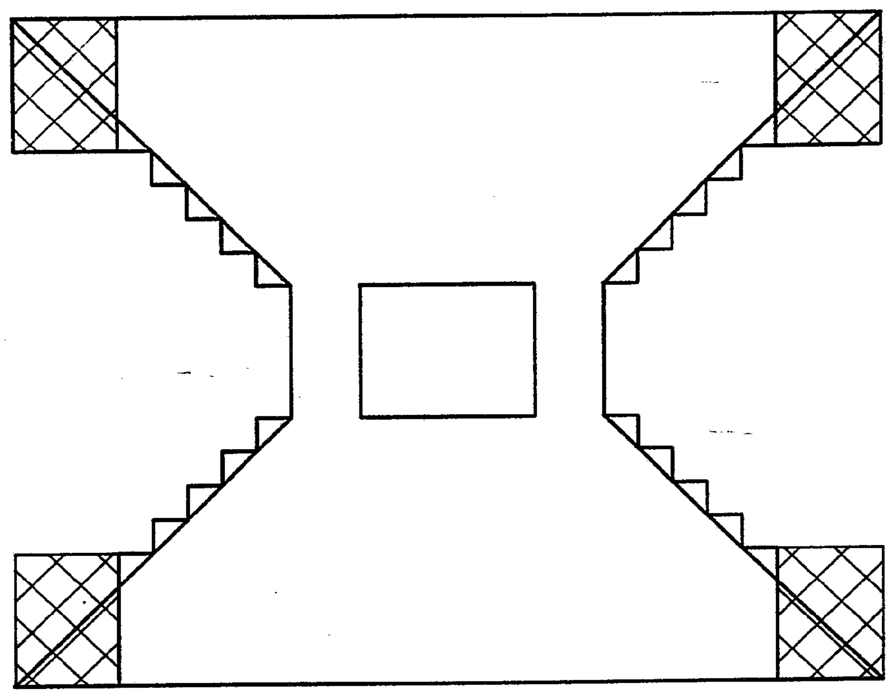


FIG. 43b

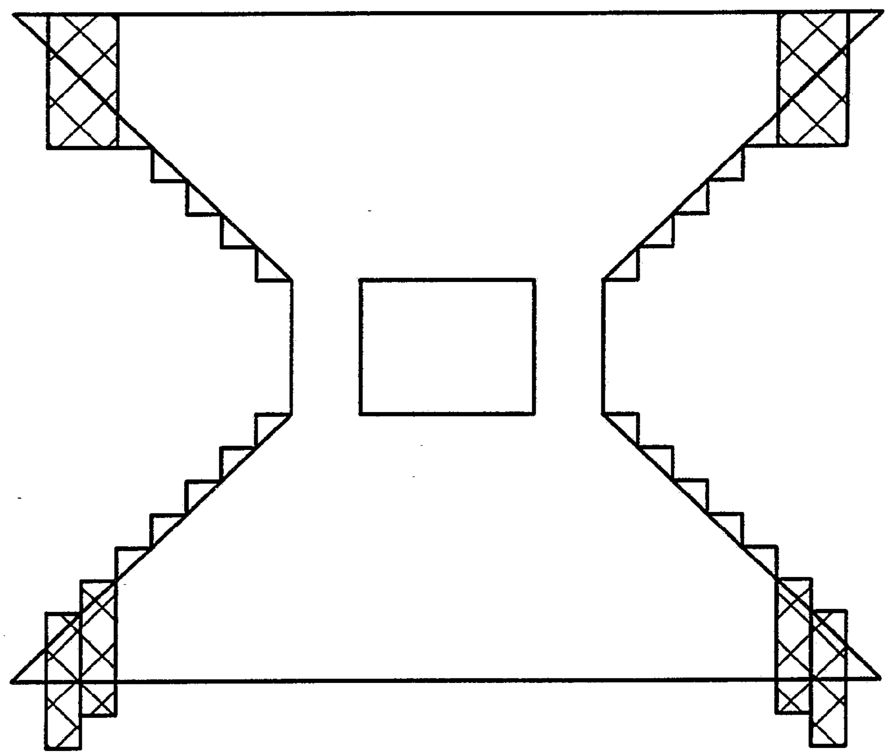


FIG. 43c

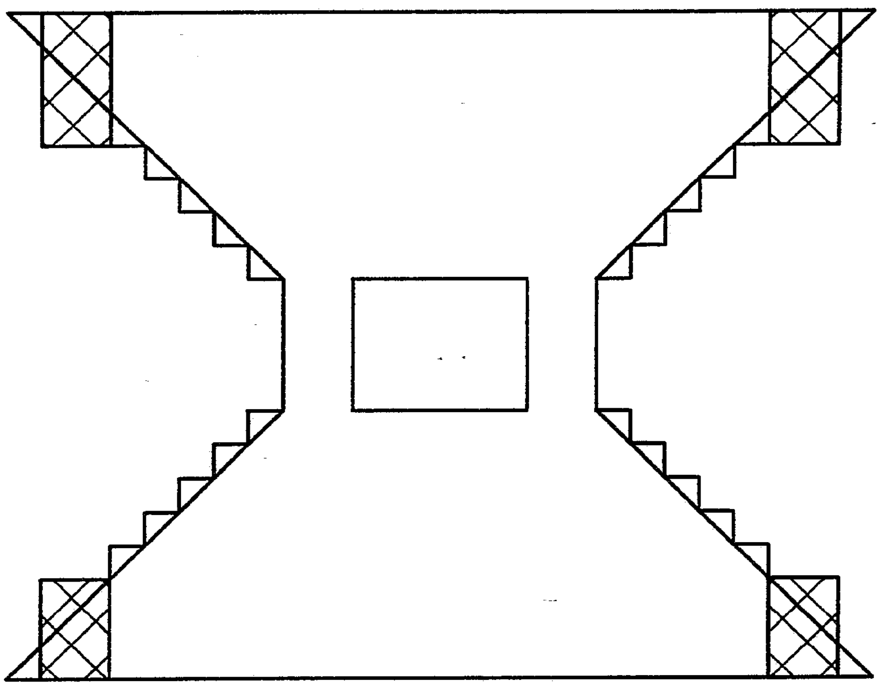


FIG. 43d

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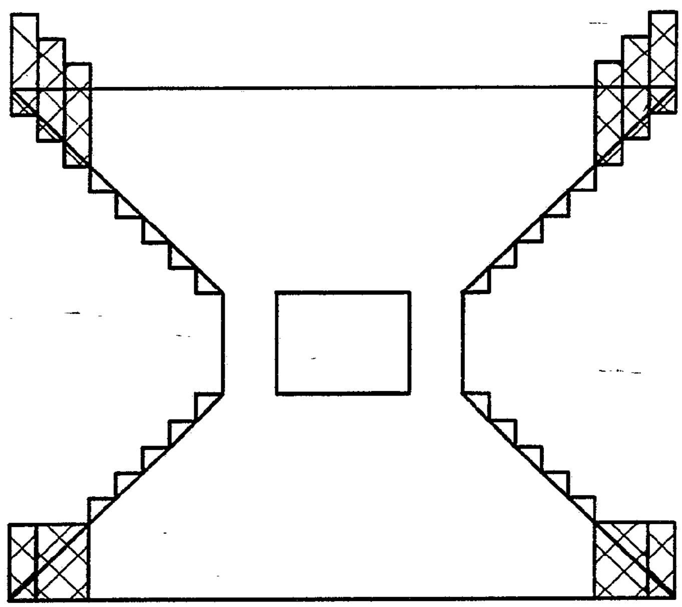

FIG. 43e

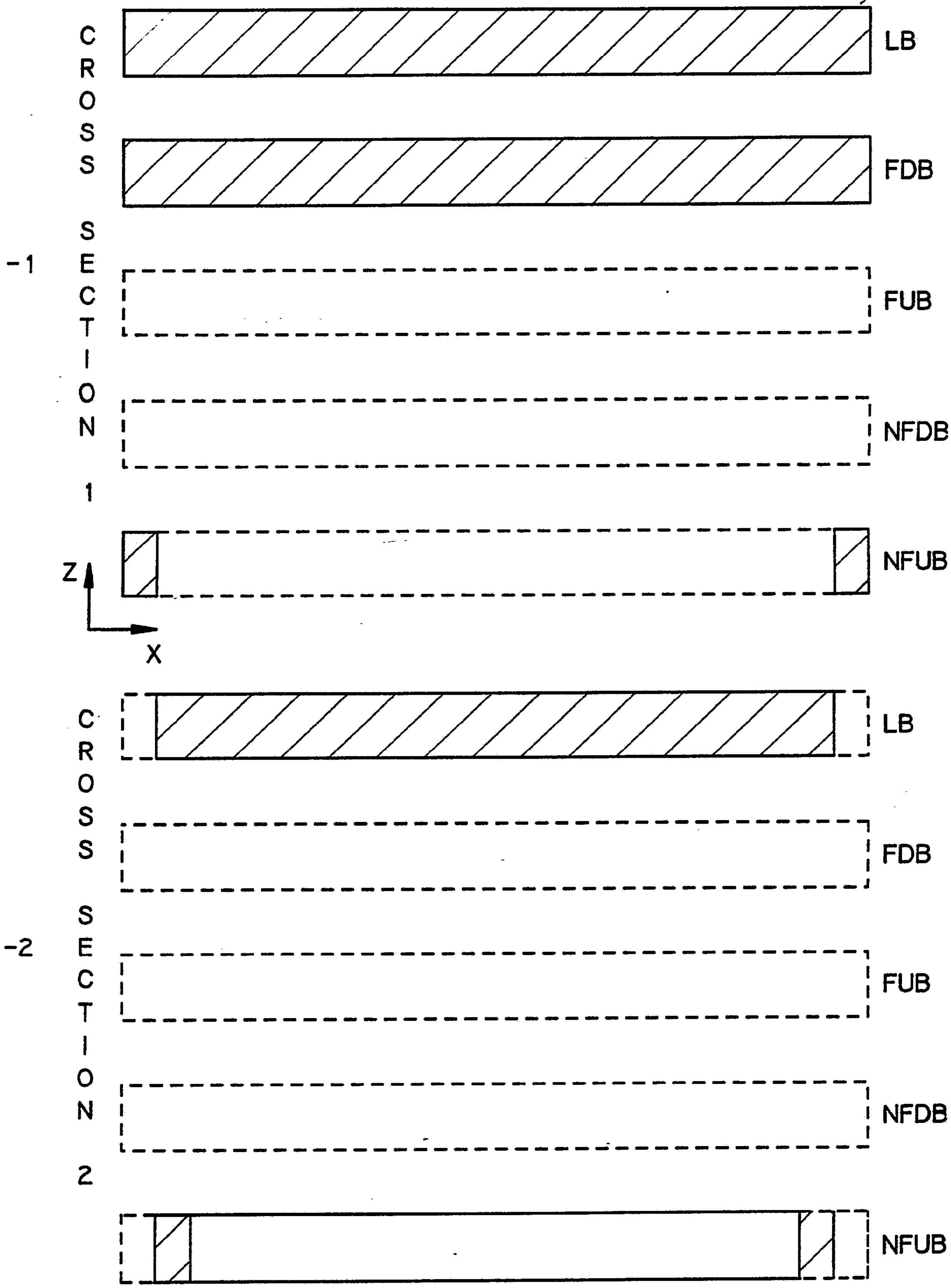
CROSS SECTION -1 1
LB
FDB
FUB
NFDB
NFUB
Z
X
CROSS SECTION -2 2
LB
FDB
FUB
NFDB
NFUB

FIG. 44

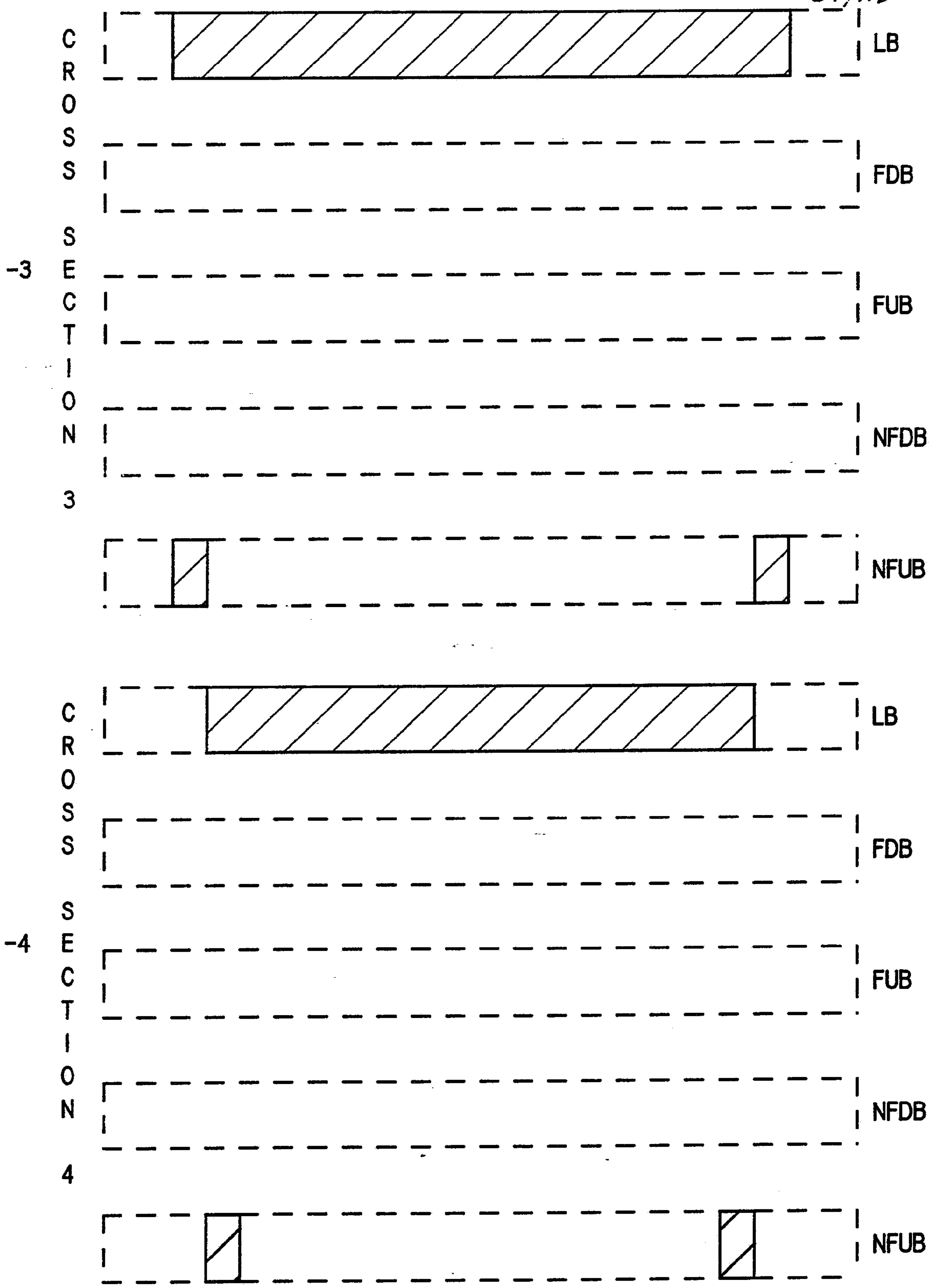
CROSS SECTION 3
-3
LB
FDB
FUB
NFDB
NFUB
CROSS SECTION 4
-4
LB
FDB
FUB
NFDB
NFUB

FIG. 44

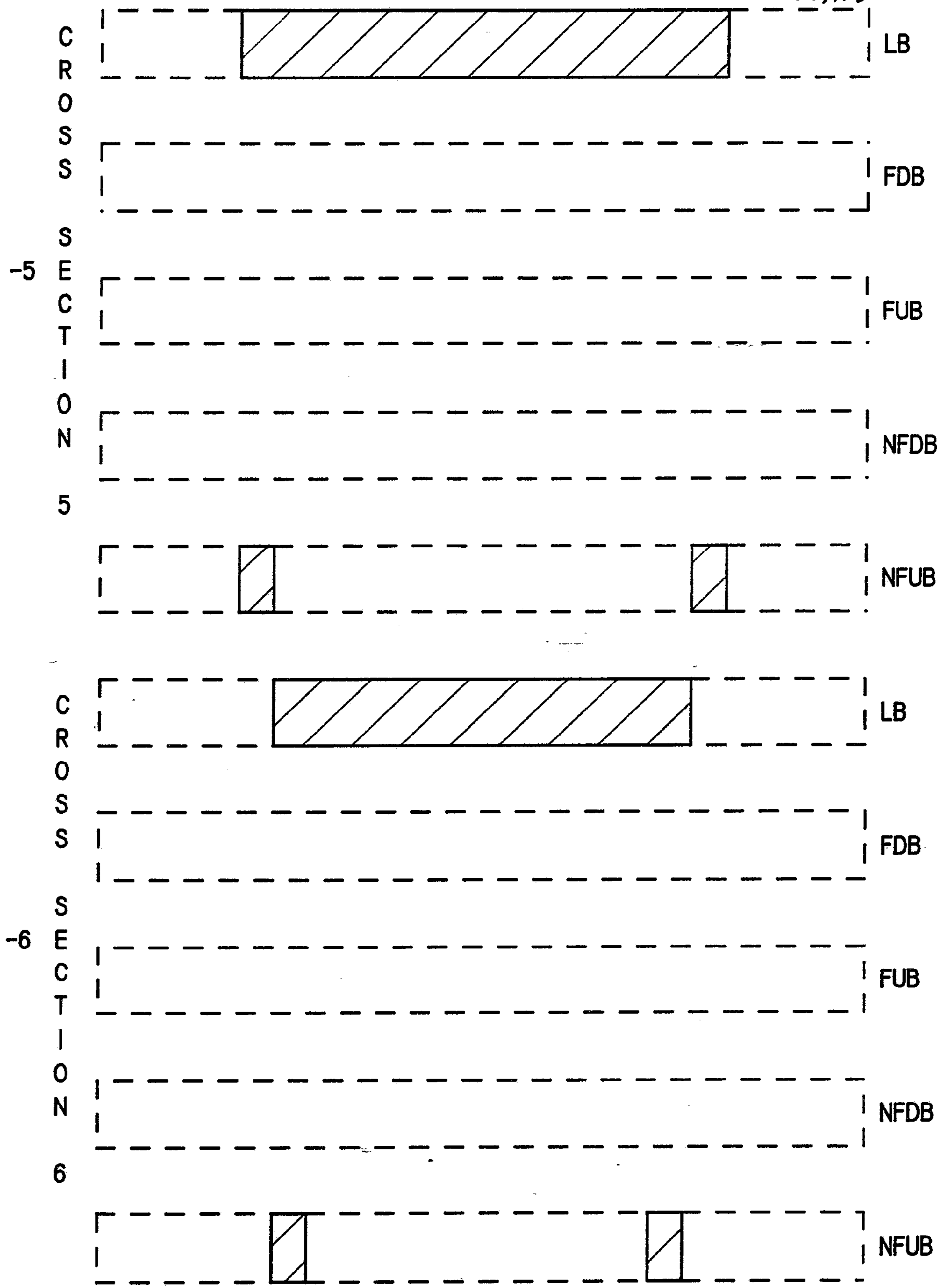
CROSS SECTION 5
-5
LB
FDB
FUB
NFDB
NFUB
CROSS SECTION 6
-6
LB
FDB
FUB
NFDB
NFUB

FIG. 44

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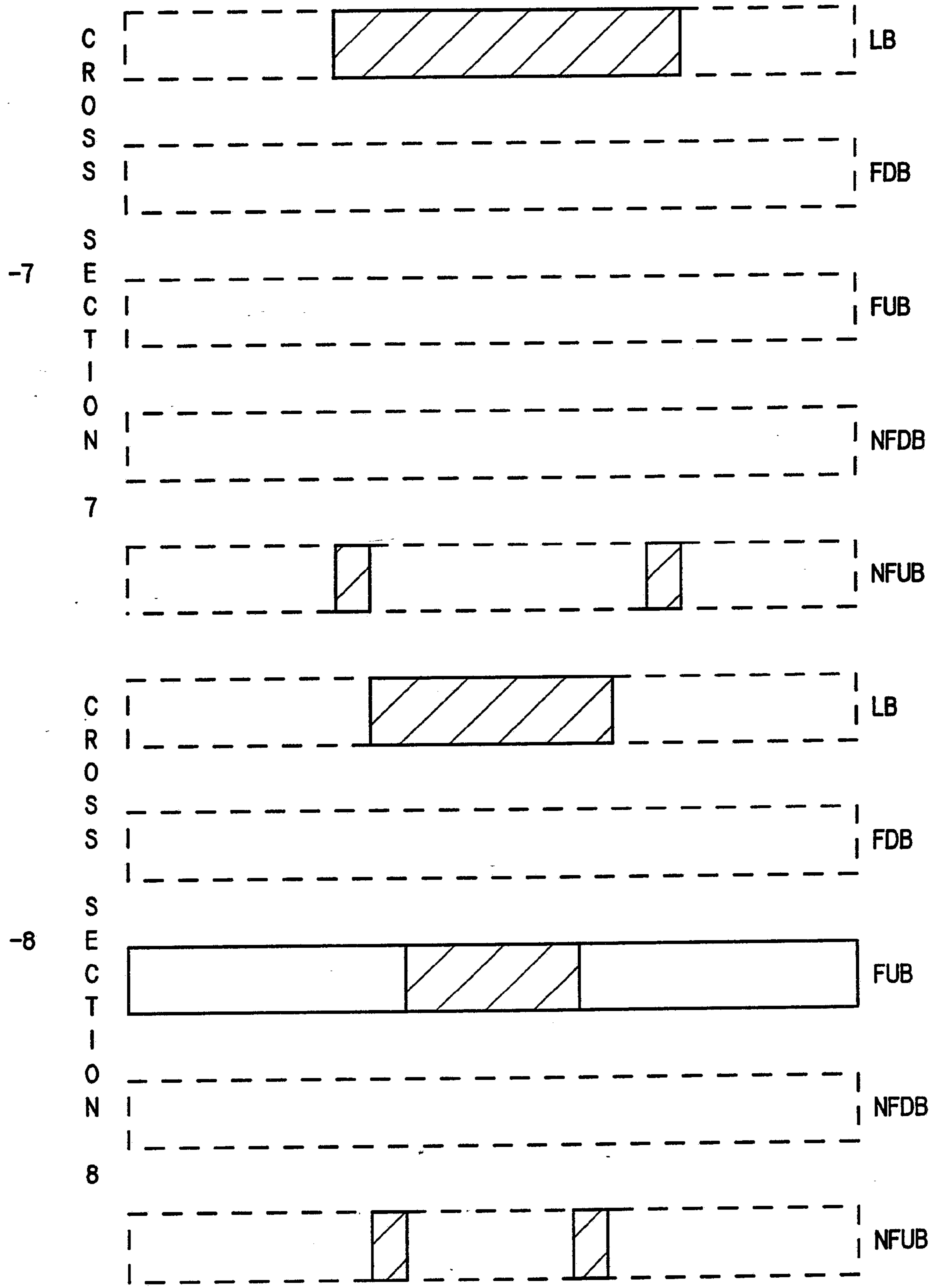
CROSS SECTION 7
-7
LB
FDB
FUB
NFDB
NFUB
CROSS SECTION 8
-8
LB
FDB
FUB
NFDB
NFUB

FIG. 44

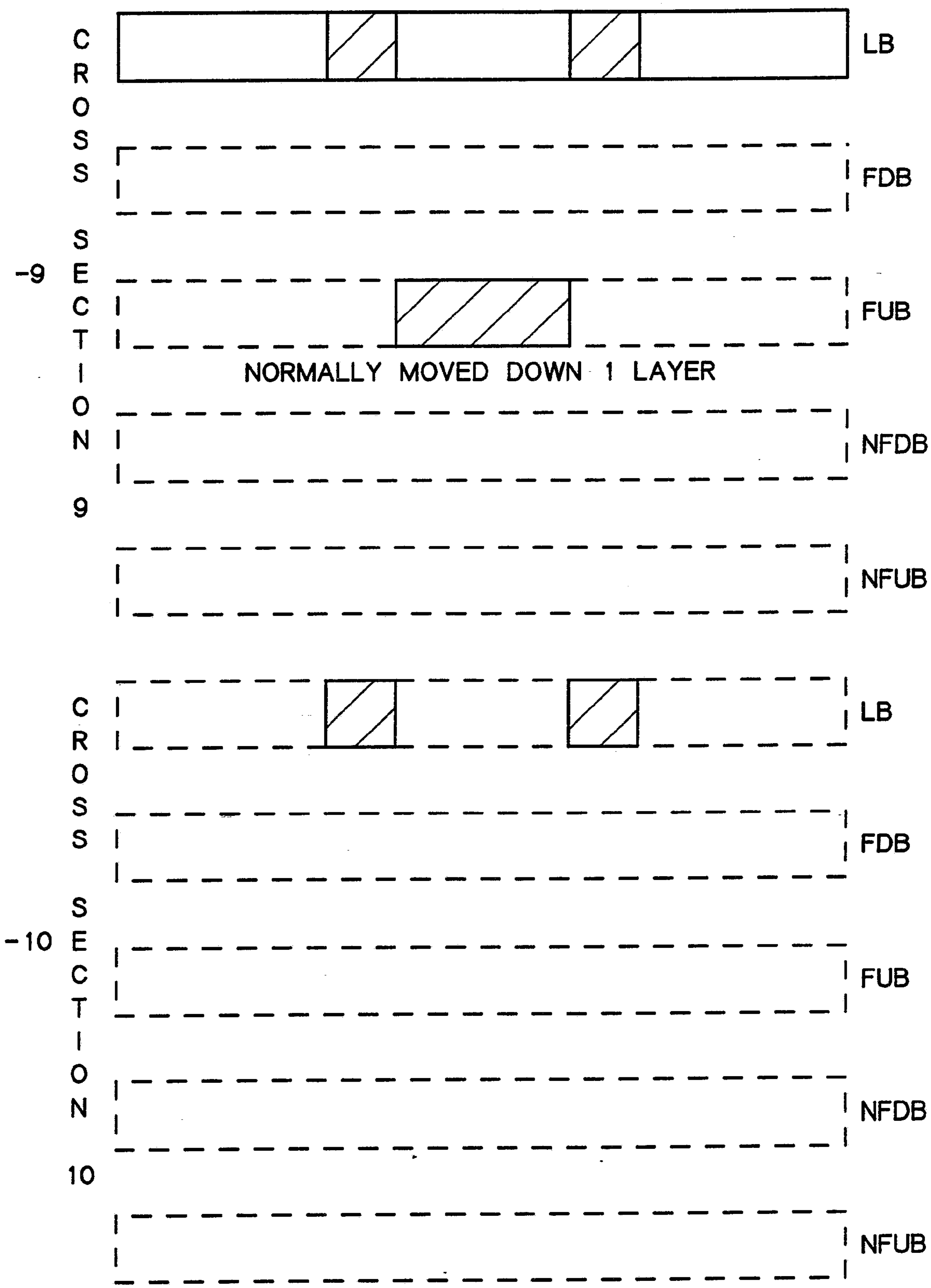
CROSS SECTION -9 9
LB
FDB
FUB
NORMALLY MOVED DOWN 1 LAYER
NFDB
NFUB
CROSS SECTION -10 10
LB
FDB
FUB
NFDB
NFUB

FIG. 44

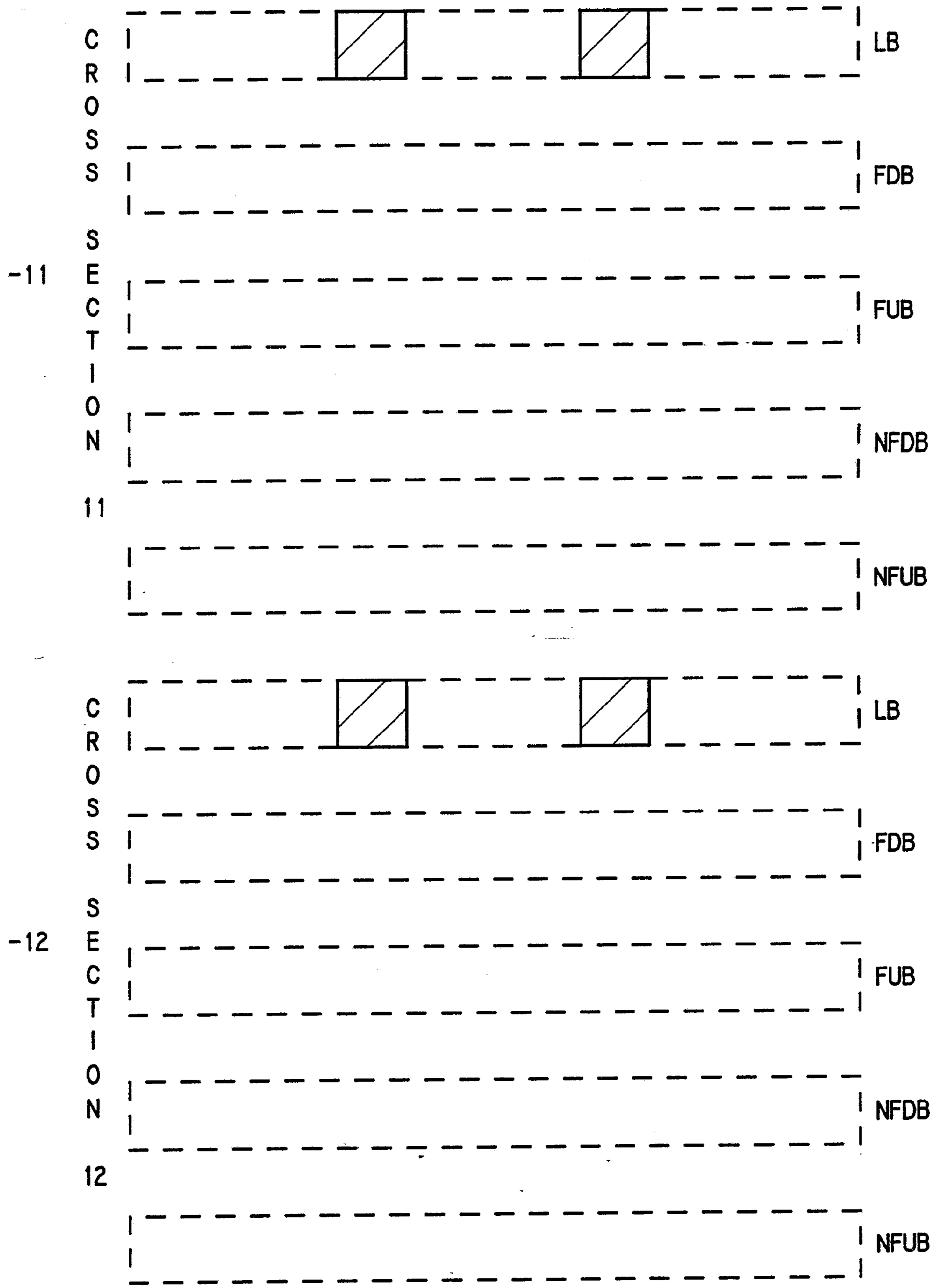
CROSS SECTION 11
-11
LB
FDB
FUB
NFDB
NFUB
CROSS SECTION 12
-12
LB
FDB
FUB
NFDB
NFUB

FIG. 44

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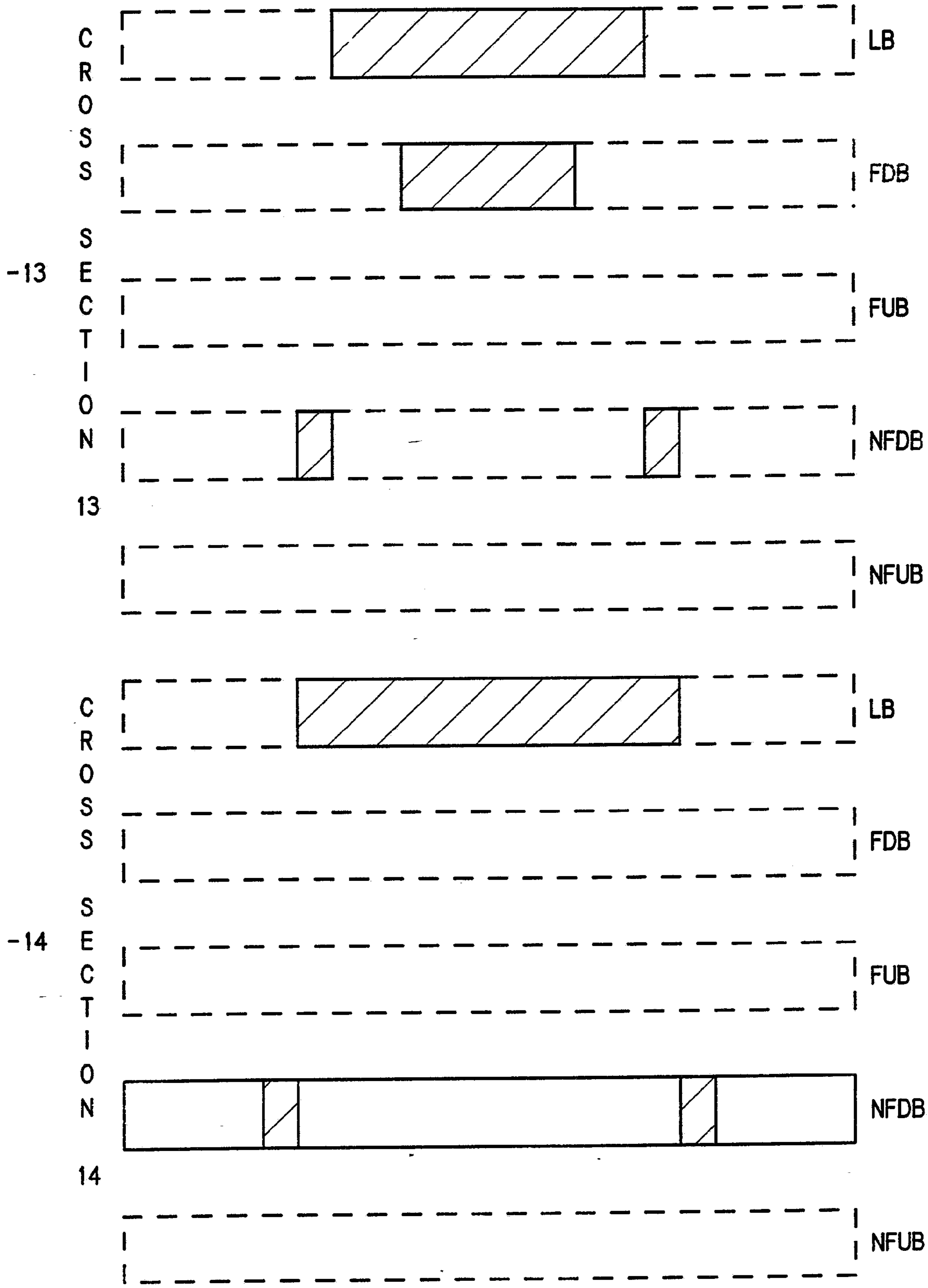
CROSS SECTION -13 13
LB
FDB
FUB
NFDB
NFUB
CROSS SECTION -14 14
LB
FDB
FUB
NFDB
NFUB

FIG. 44

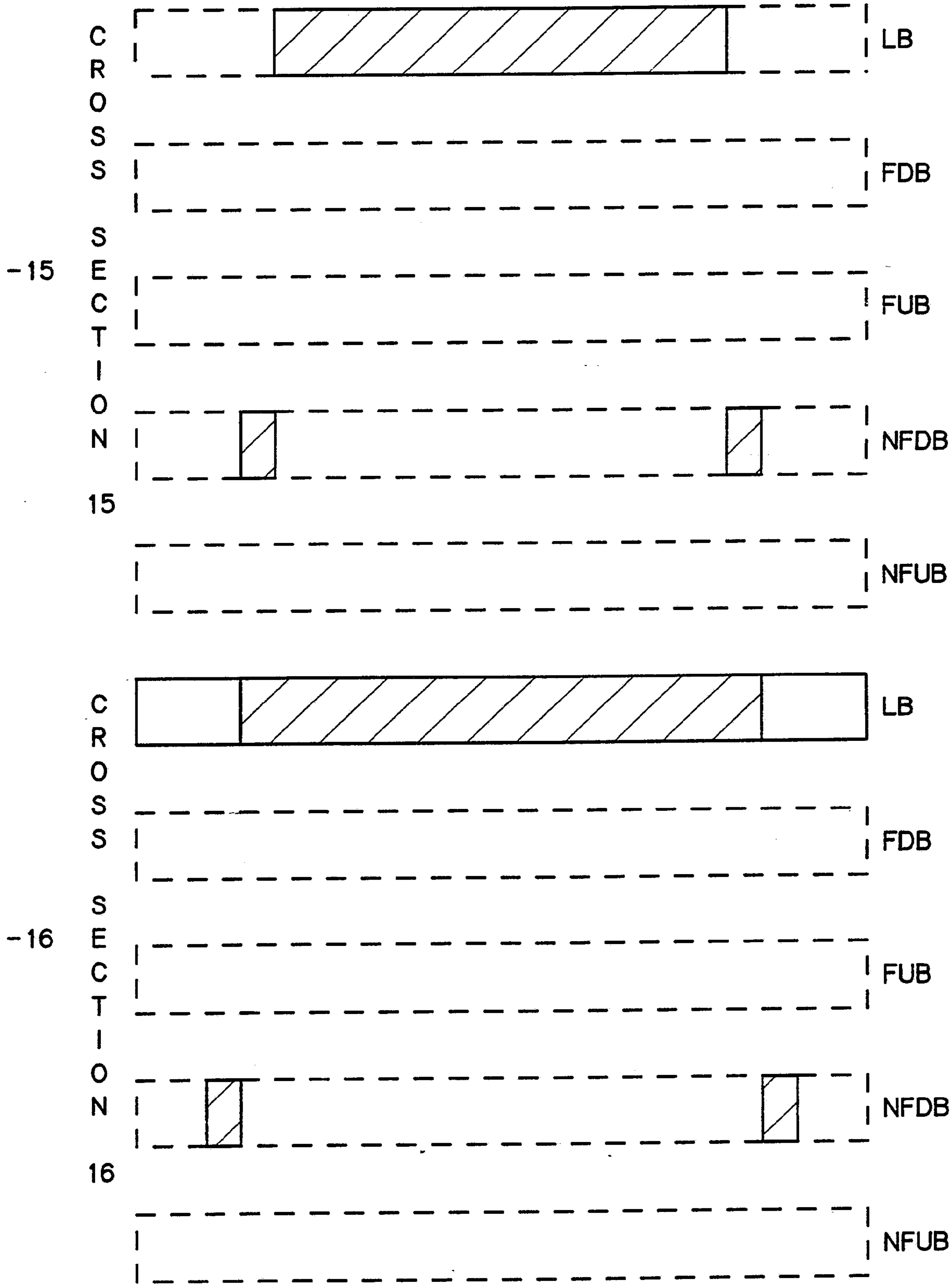
CROSS SECTION -15 15
LB
FDB
FUB
NFDB
NFUB
CROSS SECTION -16 16
LB
FDB
FUB
NFDB
NFUB

FIG. 44

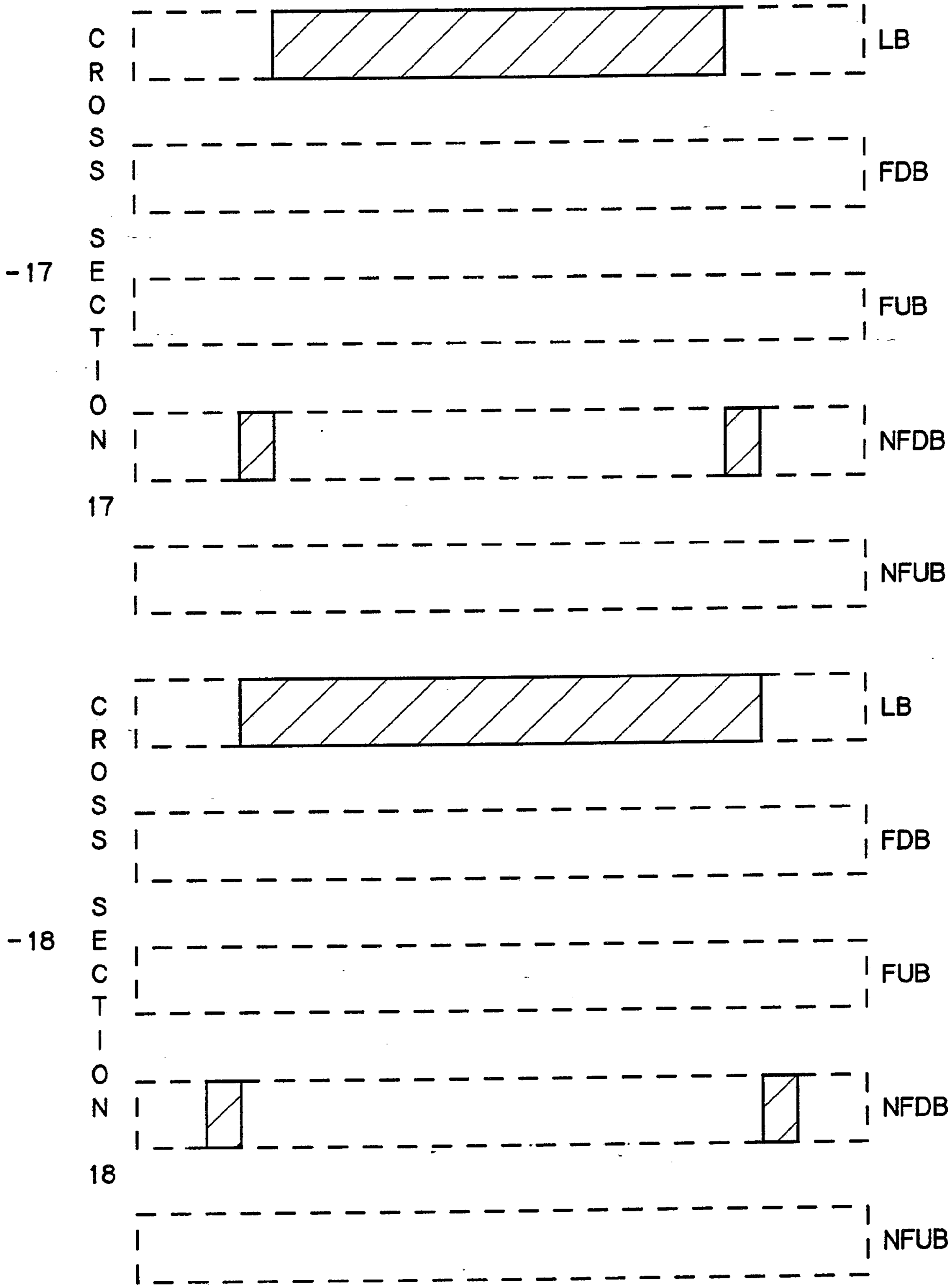
CROSS SECTION -17 17
LB
FDB
FUB
NFDB
NFUB
CROSS SECTION -18 18
LB
FDB
FUB
NFDB
NFUB

FIG. 44

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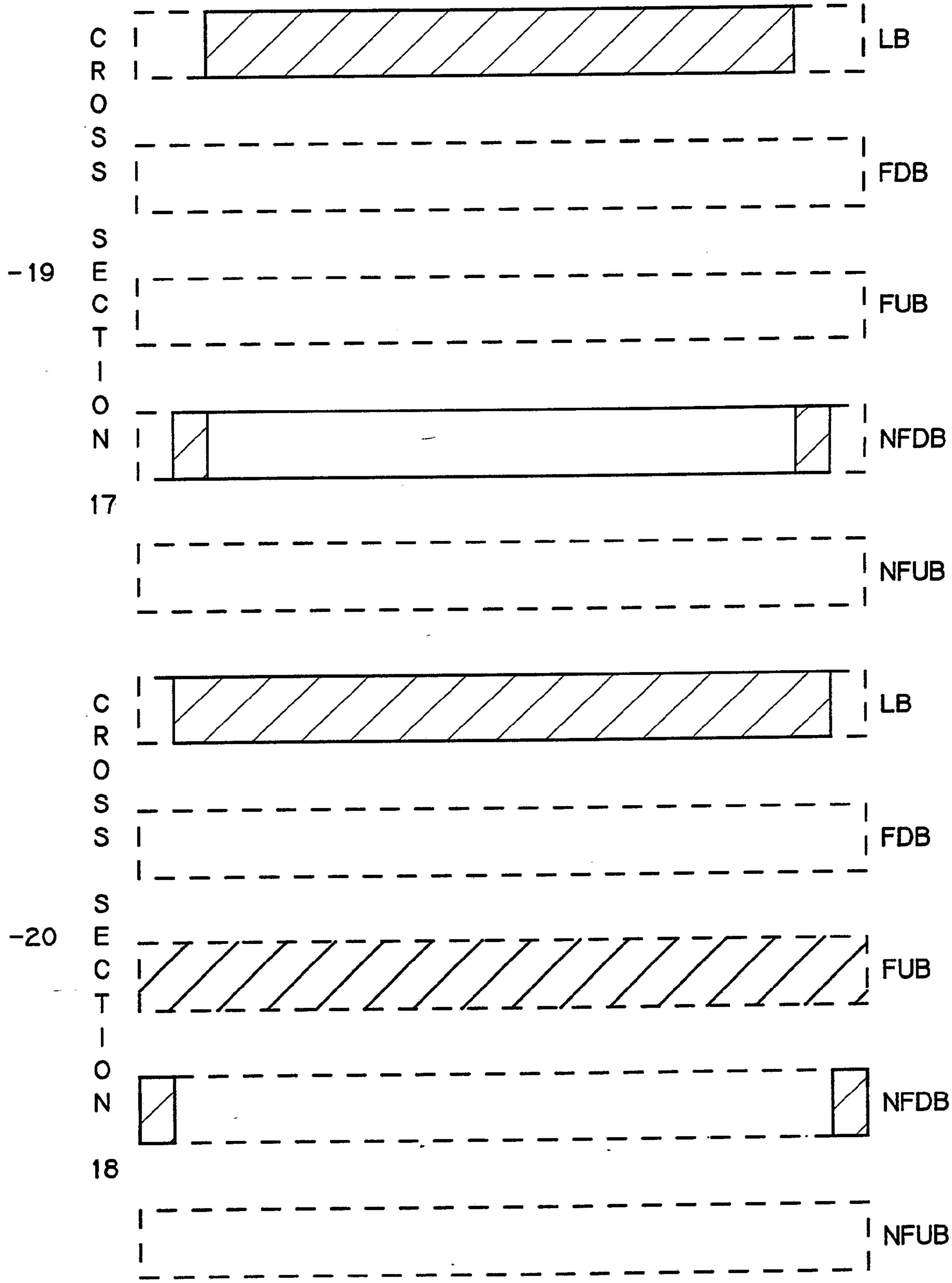
CROSS SECTION 17
-19
LB
FDB
FUB
NFDB
NFUB
CROSS SECTION 18
-20
LB
FDB
FUB
NFDB
NFUB

FIG. 44

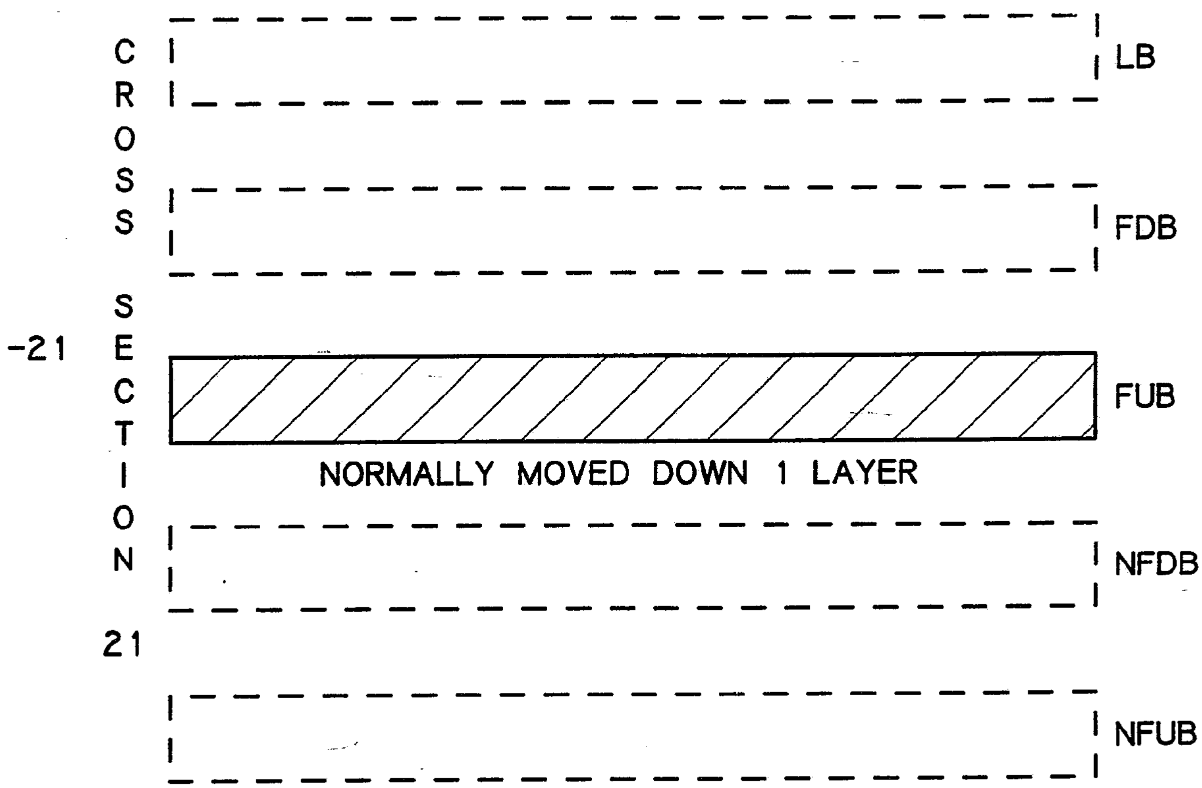
C
R
O
S
S
S
E
C
T
I
O
N
-21
21
LB
FDB
FUB
NORMALLY MOVED DOWN 1 LAYER
NFDB
NFUB

FIG. 44

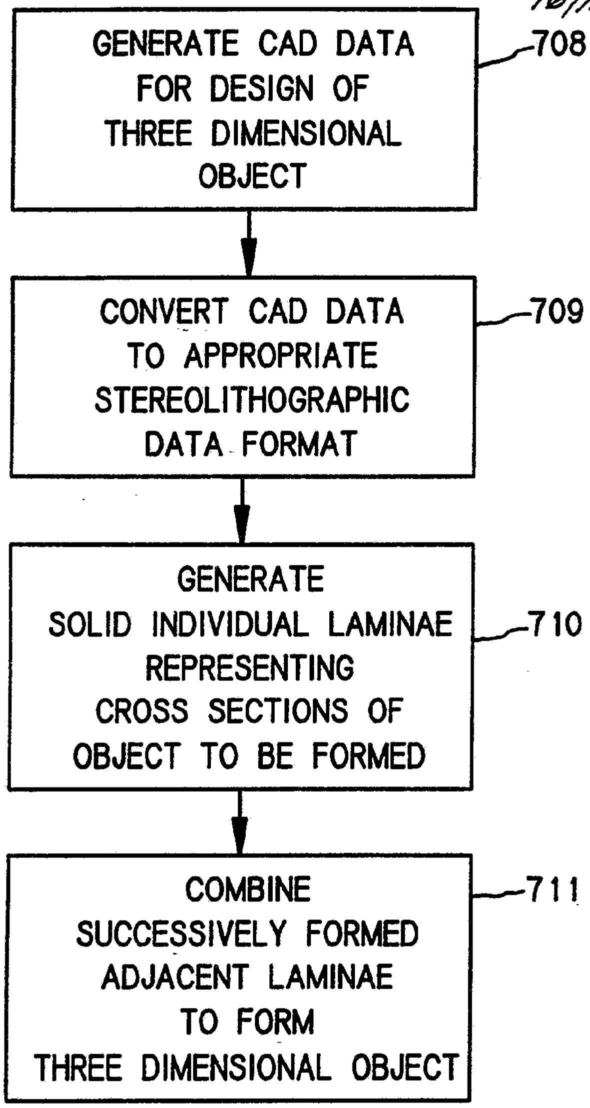
GENERATE CAD DATA FOR DESIGN OF THREE DIMENSIONAL OBJECT
708
CONVERT CAD DATA TO APPROPRIATE STEREOLITHOGRAPHIC DATA FORMAT
709
GENERATE SOLID INDIVIDUAL LAMINAE REPRESENTING CROSS SECTIONS OF OBJECT TO BE FORMED
710
COMBINE SUCCESSIVELY FORMED ADJACENT LAMINAE TO FORM THREE DIMENSIONAL OBJECT
711

FIG. 45

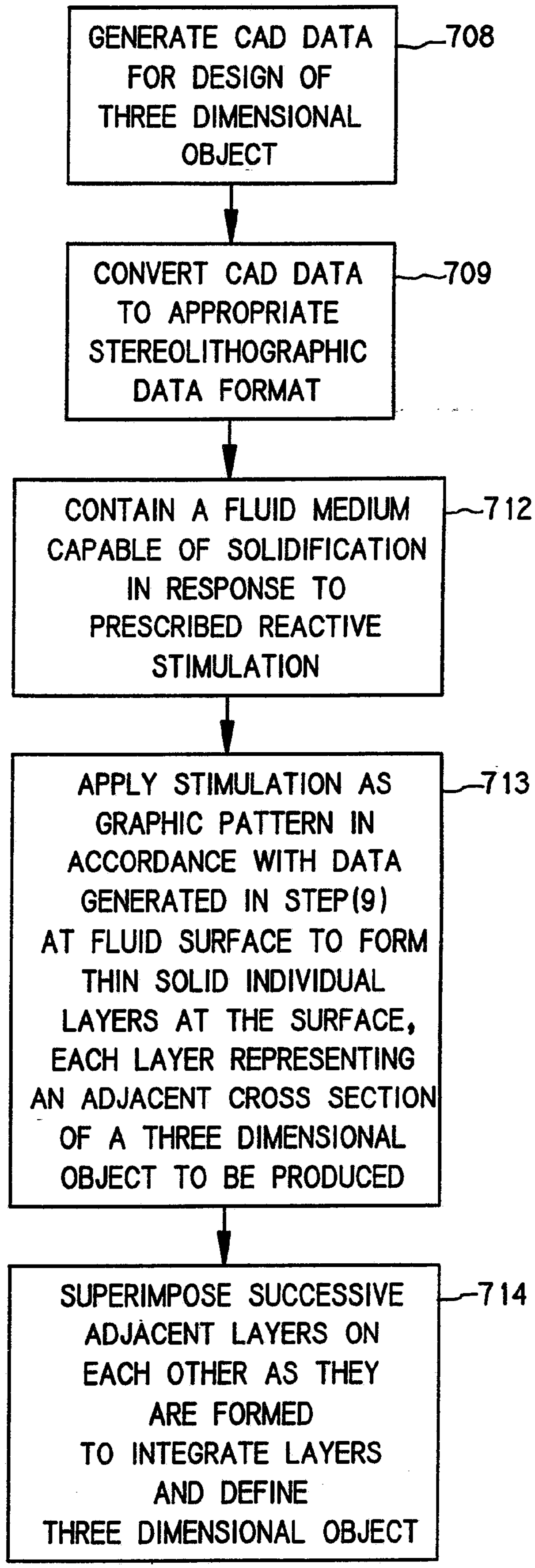
GENERATE CAD DATA FOR DESIGN OF THREE DIMENSIONAL OBJECT
708
CONVERT CAD DATA TO APPROPRIATE STEREOLITHOGRAPHIC DATA FORMAT
709
CONTAIN A FLUID MEDIUM CAPABLE OF SOLIDIFICATION IN RESPONSE TO PRESCRIBED REACTIVE STIMULATION
712
APPLY STIMULATION AS GRAPHIC PATTERN IN ACCORDANCE WITH DATA GENERATED IN STEP(9) AT FLUID SURFACE TO FORM THIN SOLID INDIVIDUAL LAYERS AT THE SURFACE, EACH LAYER REPRESENTING AN ADJACENT CROSS SECTION OF A THREE DIMENSIONAL OBJECT TO BE PRODUCED
713
SUPERIMPOSE SUCCESSIVE ADJACENT LAYERS ON EACH OTHER AS THEY ARE FORMED TO INTEGRATE LAYERS AND DEFINE THREE DIMENSIONAL OBJECT
714

FIG. 46

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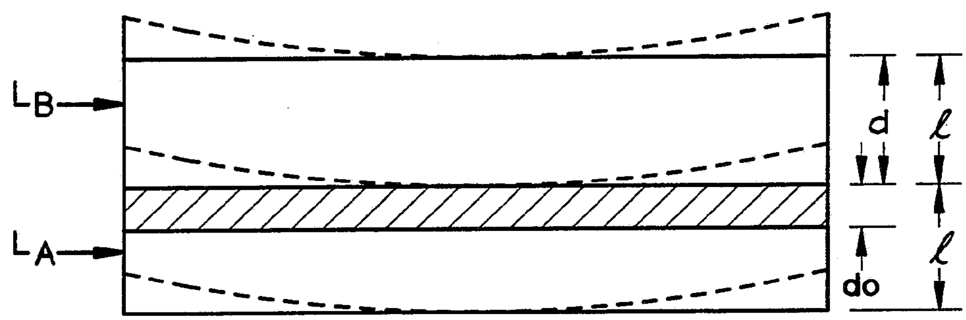


FIG. 47

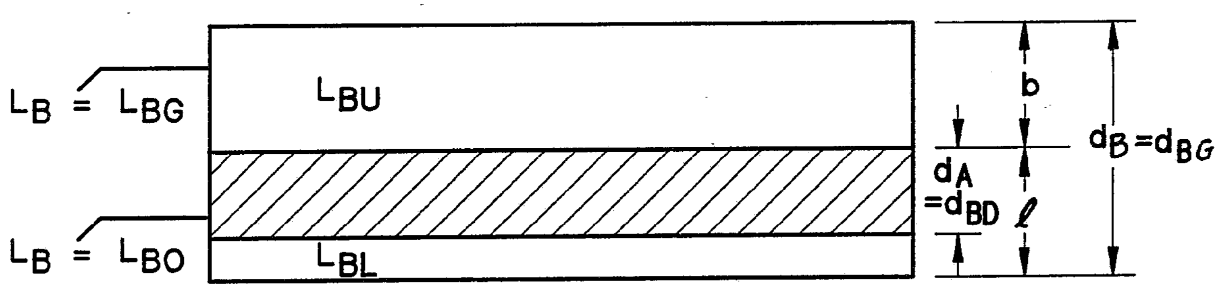
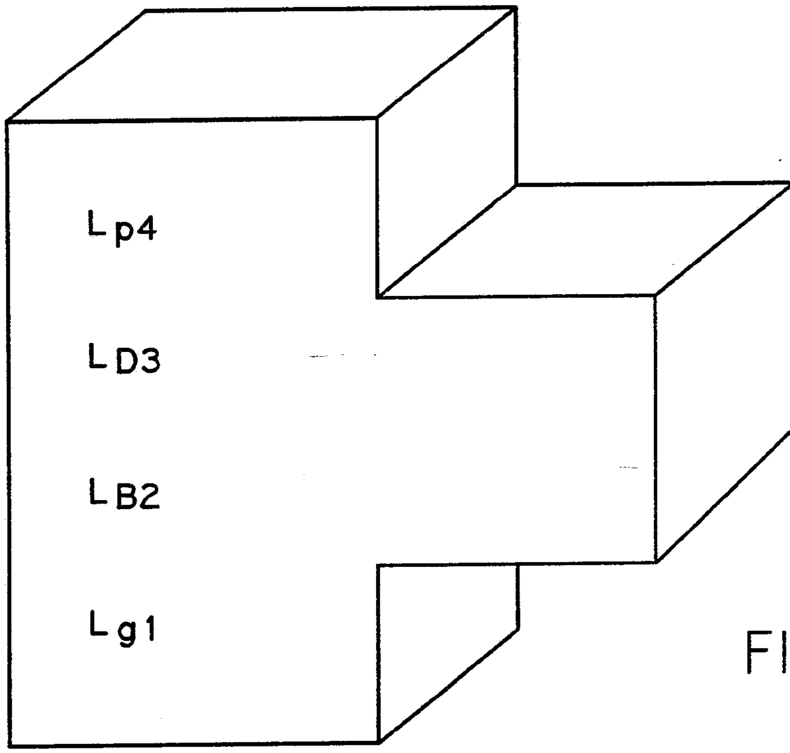
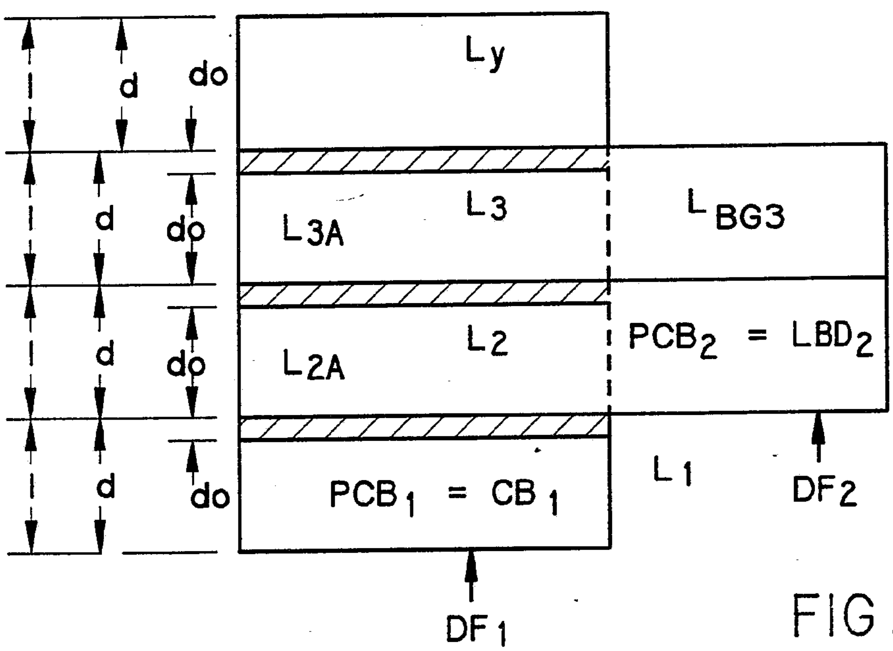


FIG. 47a



Lp4
LD3
LB2
Lg1

FIG. 48



d
do
Ly
L3A
L3
LBG3
L2A
L2
PCB2 = LBD2
L1
PCB1 = CB1
DF1
DF2

FIG. 49

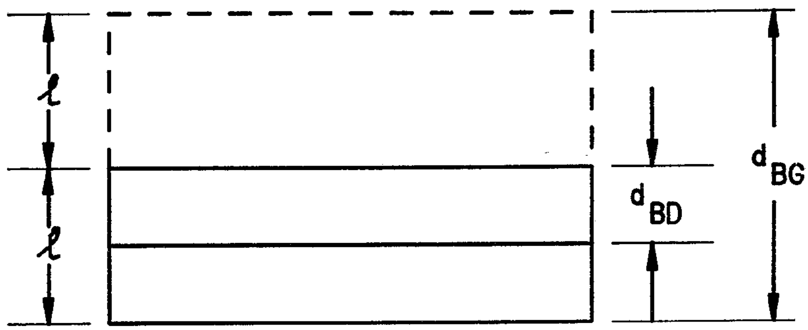


FIG. 49a

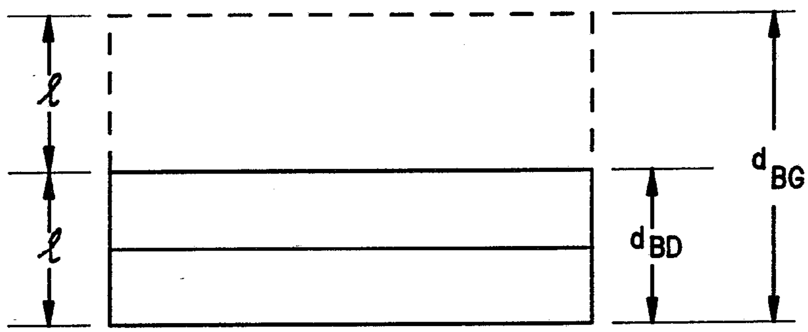


FIG. 49b

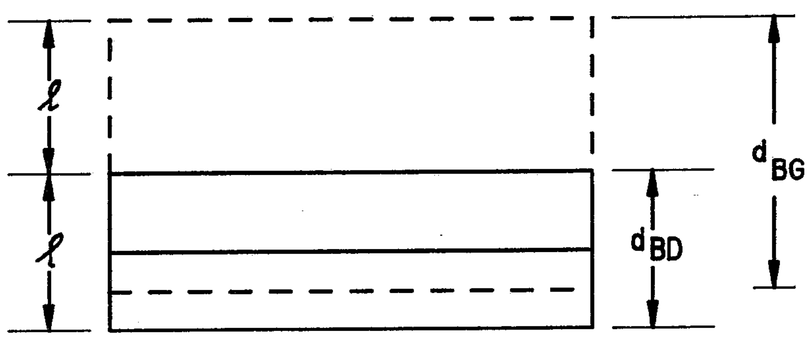


FIG. 49c

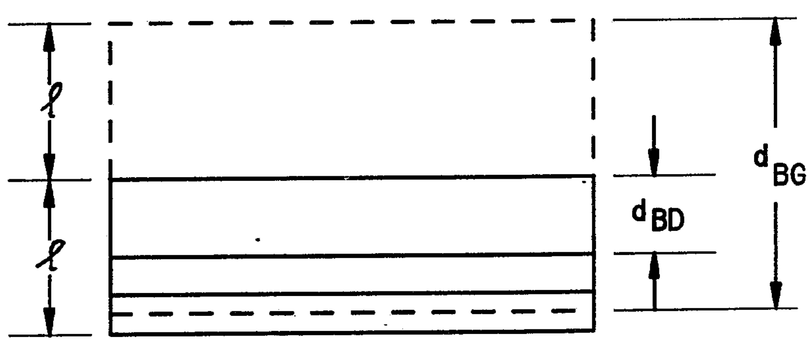


FIG. 49d

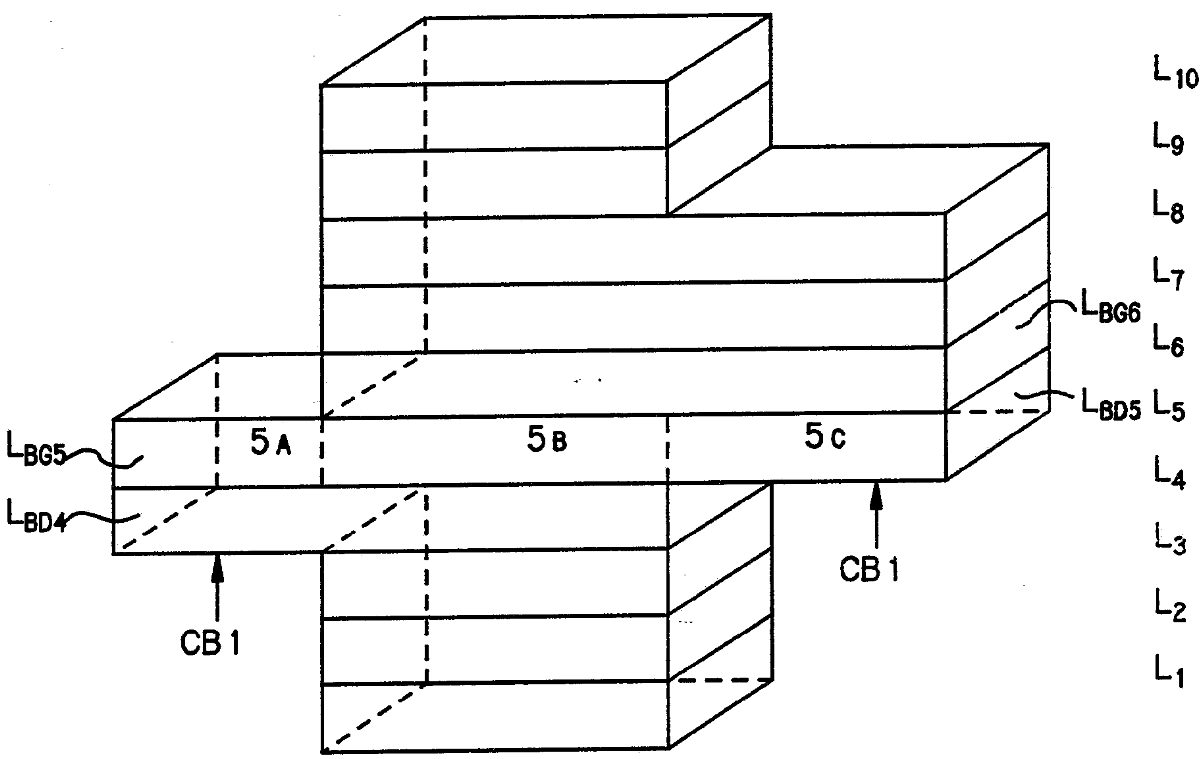


FIG. 50

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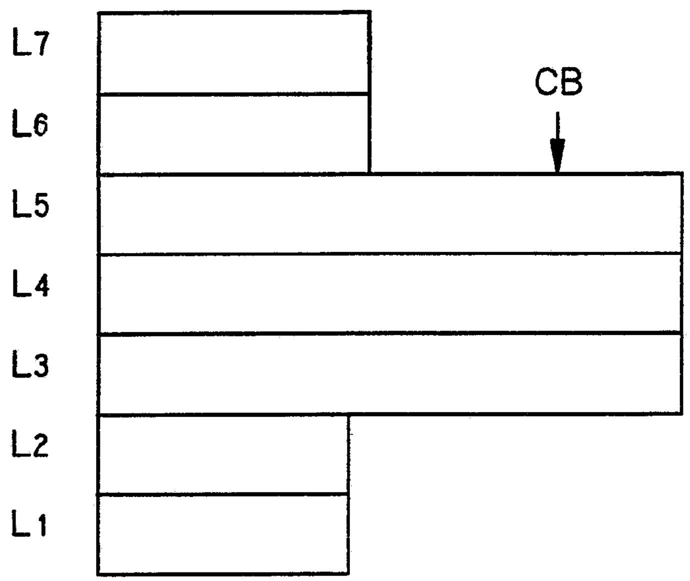

FIG. 51

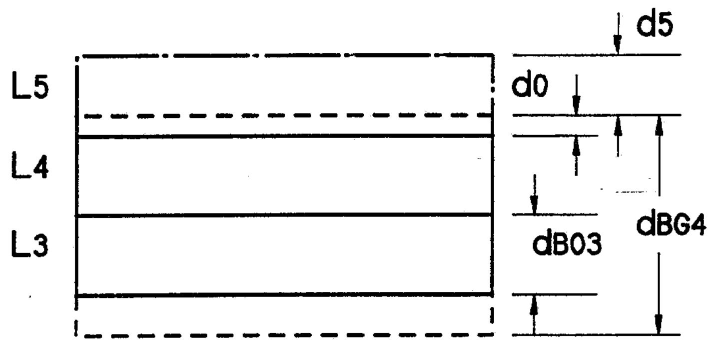

FIG. 51a

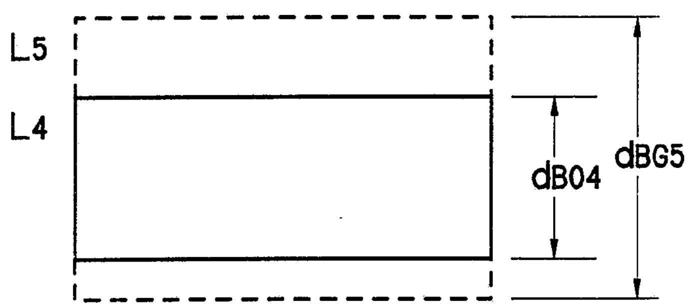

FIG. 51b

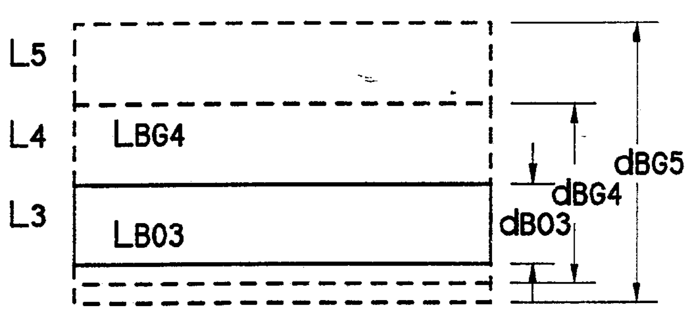

FIG. 51c

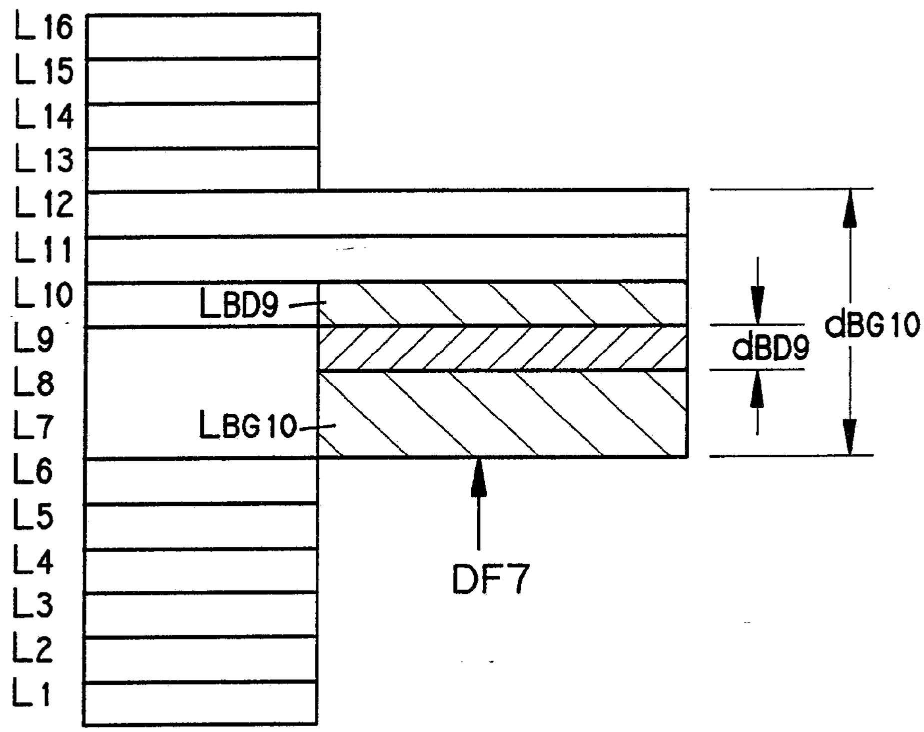
L16
L15
L14
L13
L12
L11
L10
L9
L8
L7
L6
L5
L4
L3
L2
L1
LBD9
LBG10
dBD9
dBG10
DF7

FIG. 52

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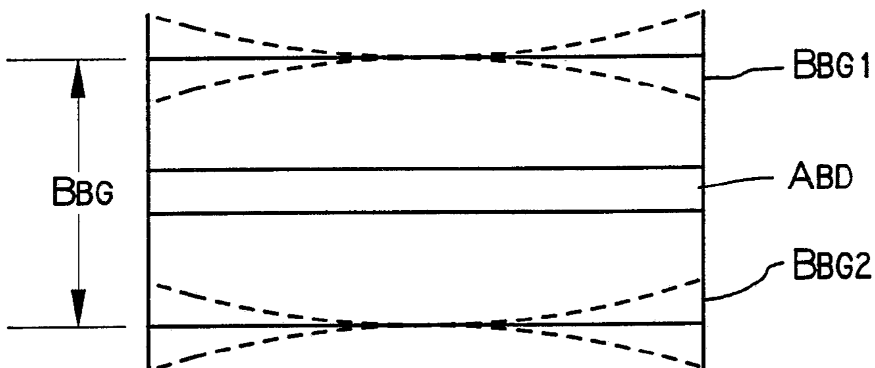

FIG. 53

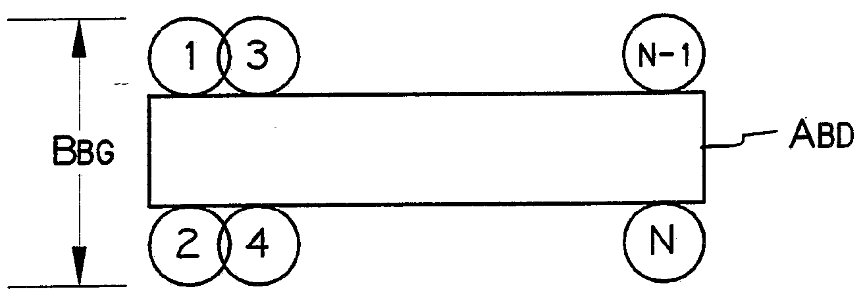

FIG. 54

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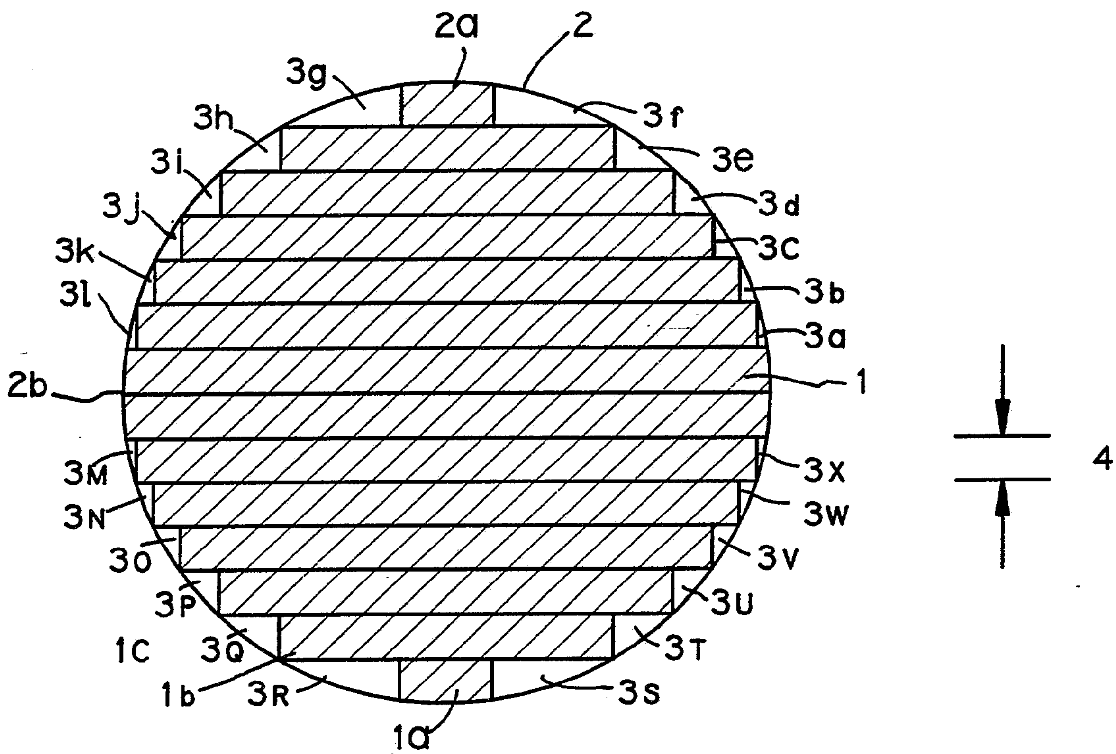
2a
2
3g
3h
3f
3e
3i
3d
3j
3C
3k
3b
3l
3a
2b
1
3M
3X
4
3N
3W
3O
3V
3P
3U
1C
3Q
3T
1b
3R
3S
1a

FIG. 55

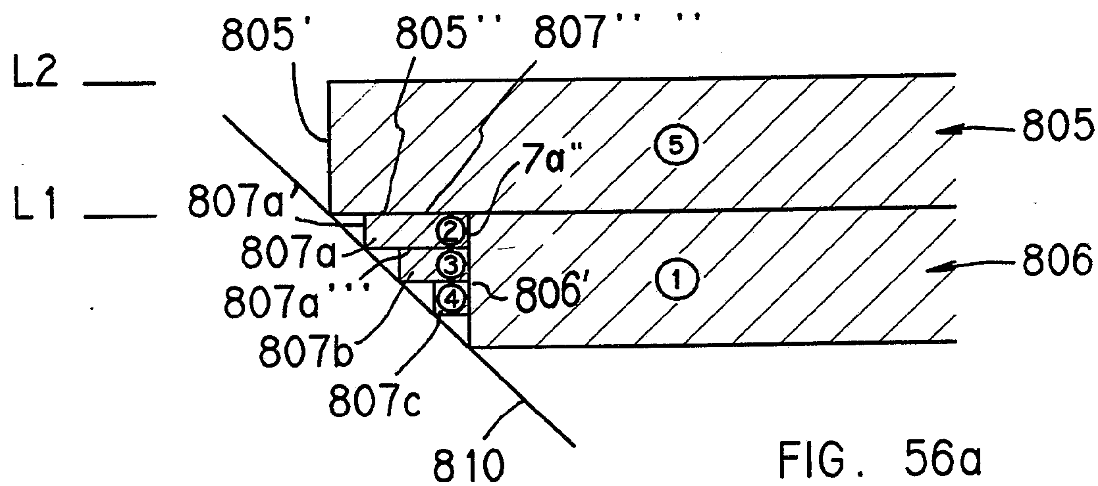

FIG. 56a

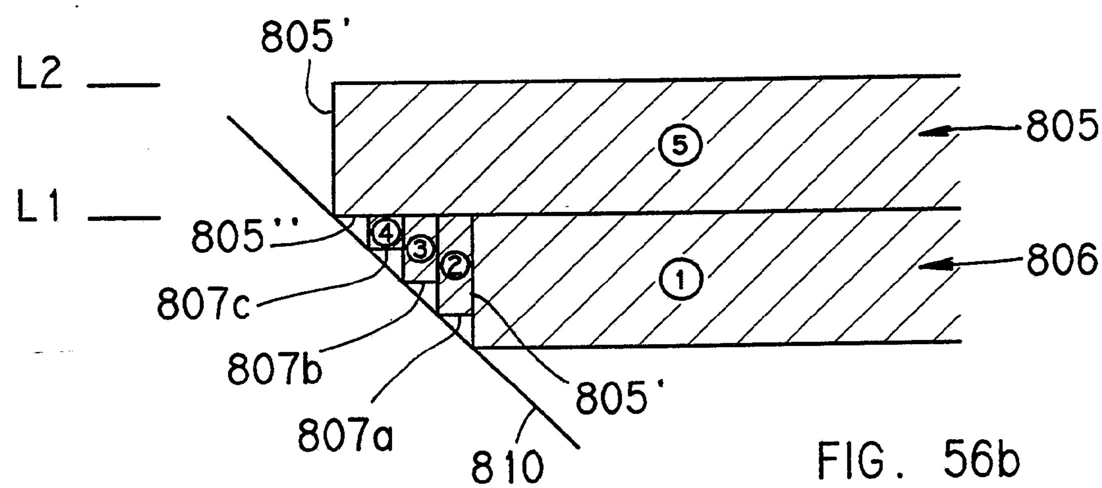

FIG. 56b

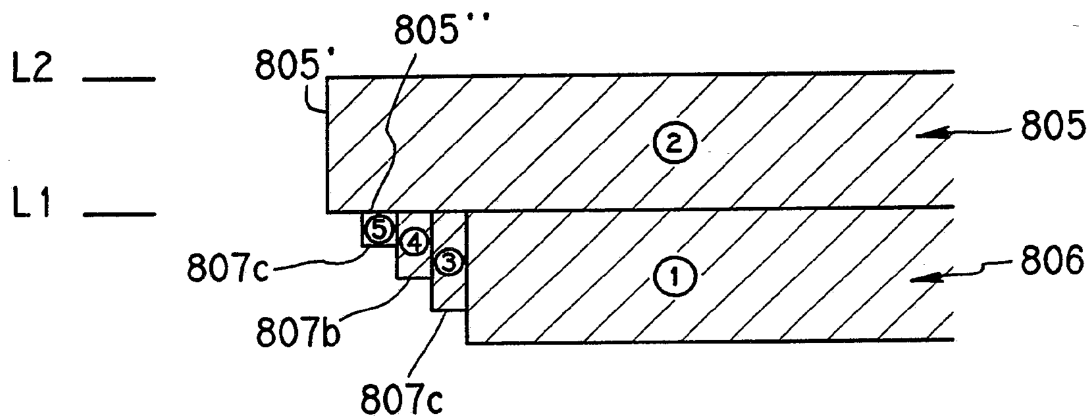

FIG. 56c

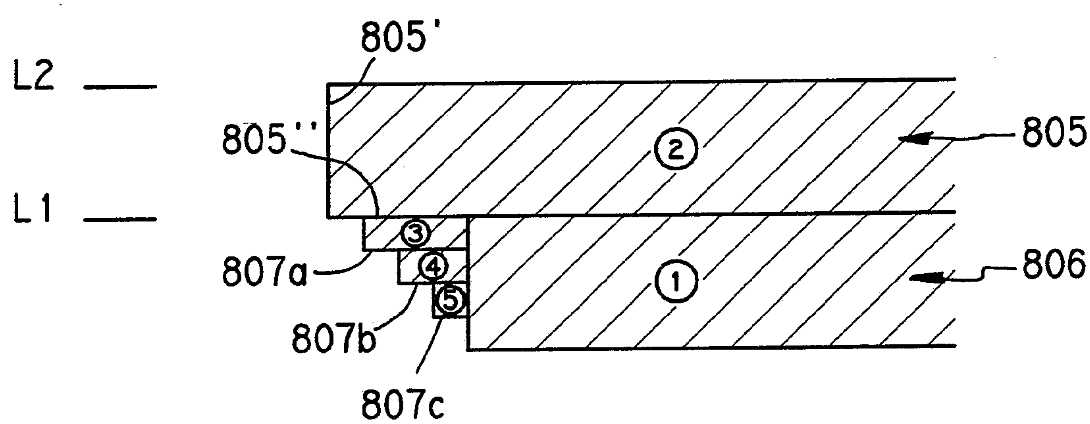

FIG. 56d

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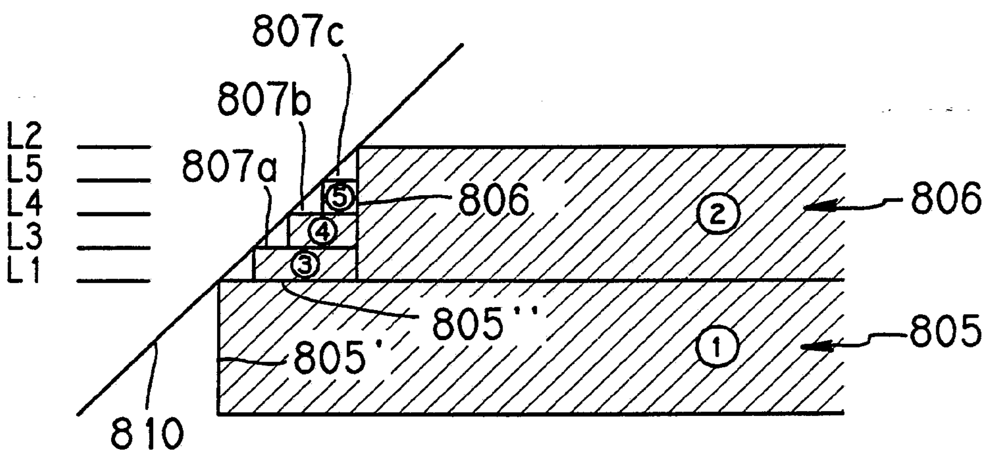


FIG. 57a

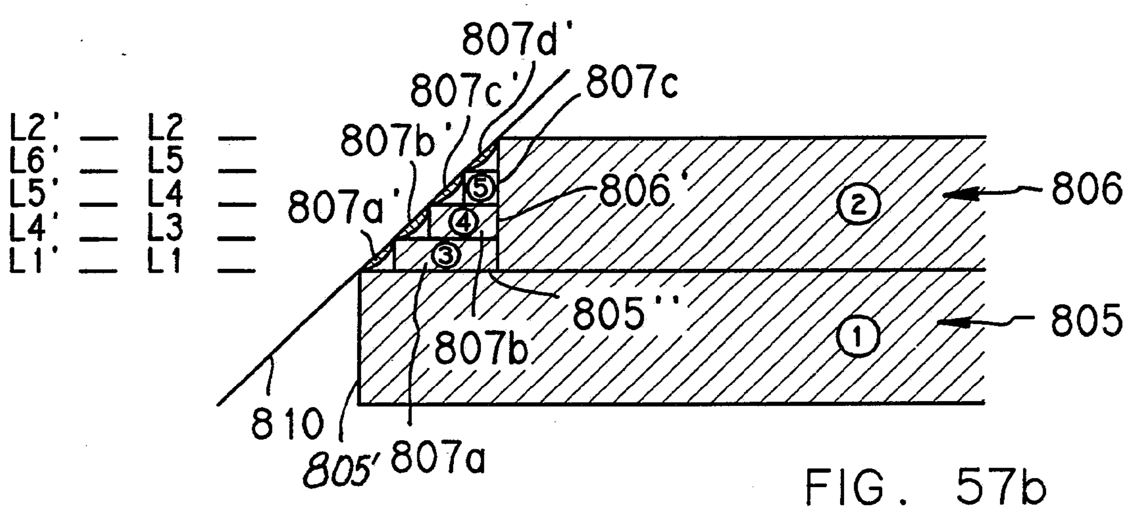


FIG. 57b

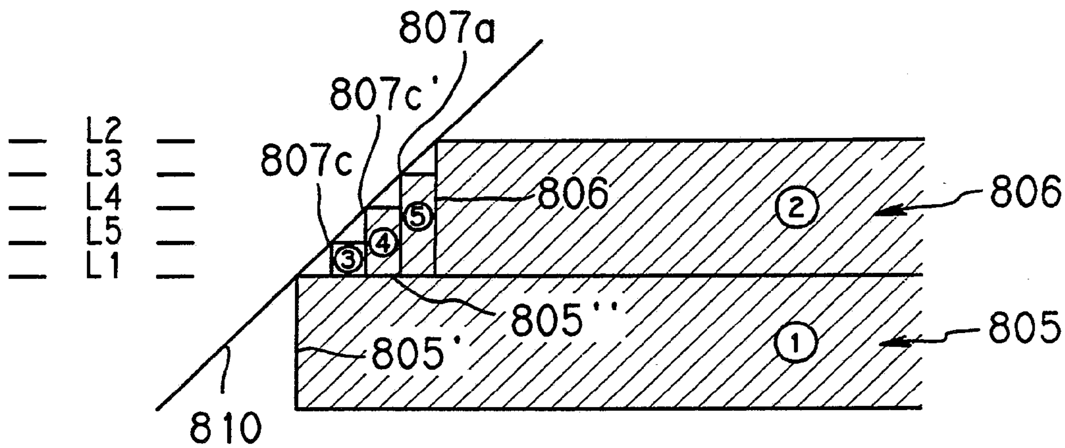


FIG. 57c

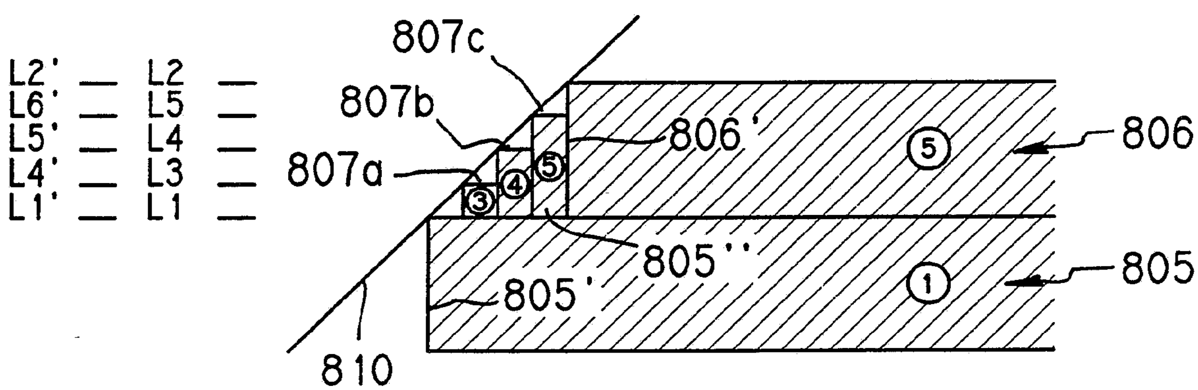


FIG. 57d

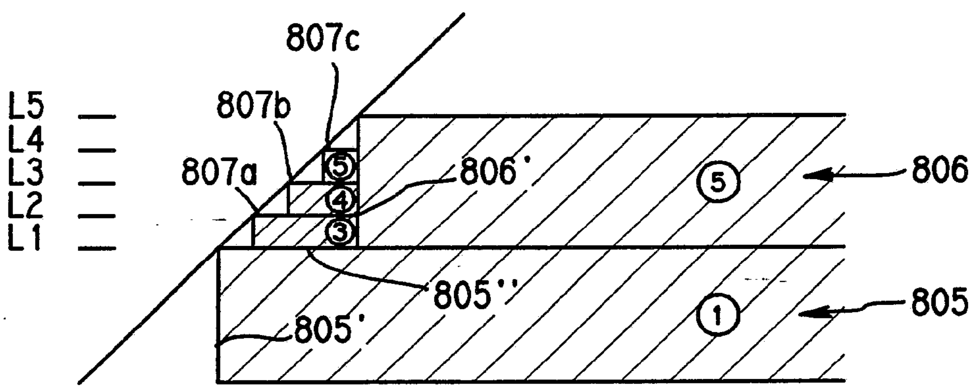


FIG. 57e

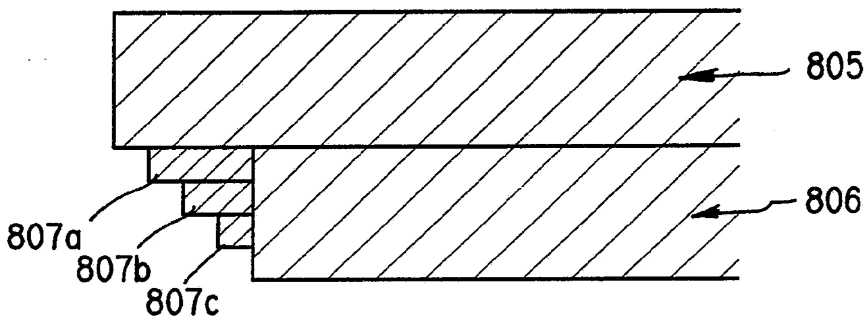


FIG. 58a

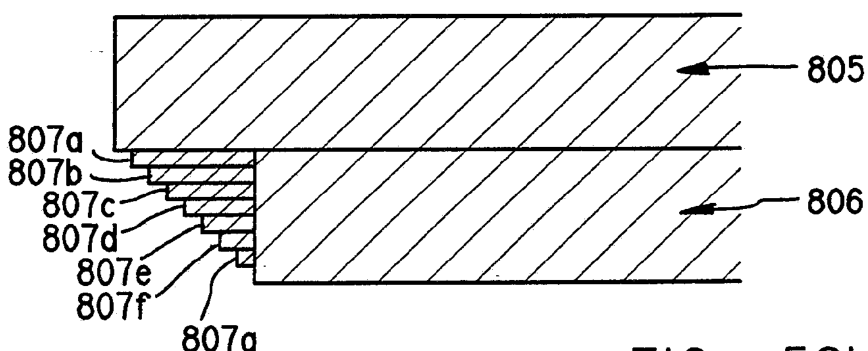


FIG. 58b

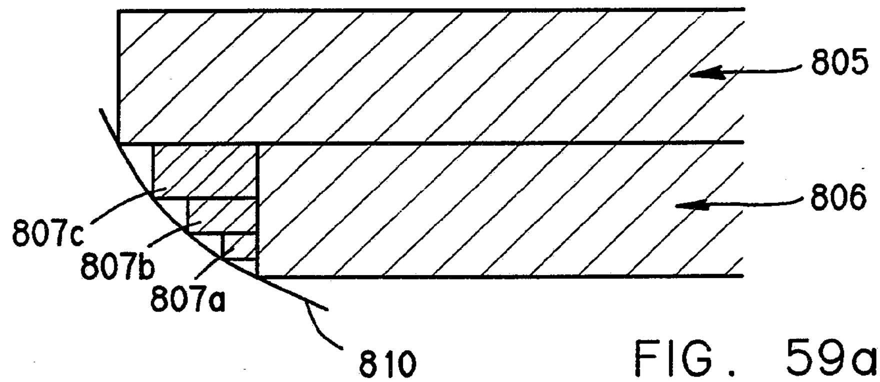


FIG. 59a

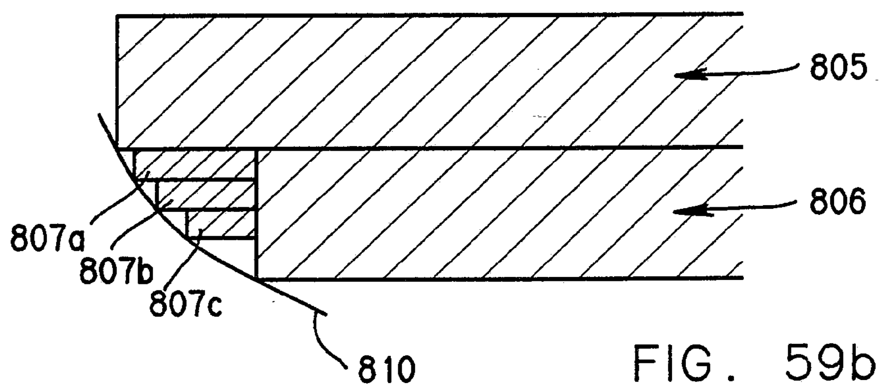


FIG. 59b

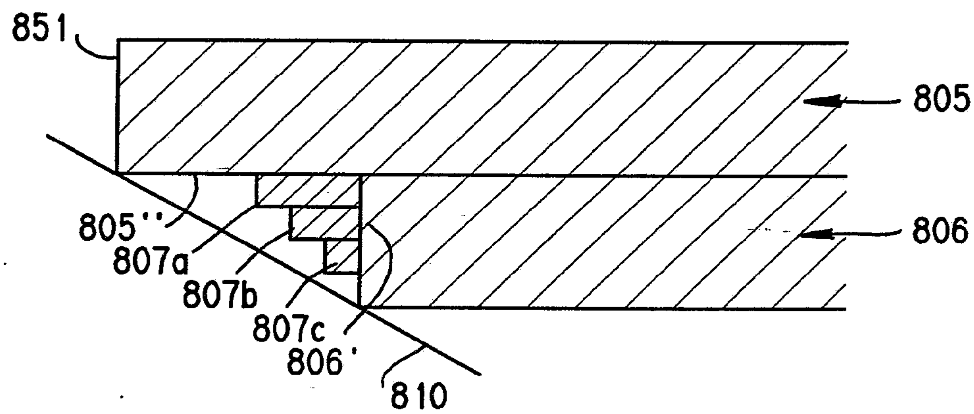


FIG. 59c

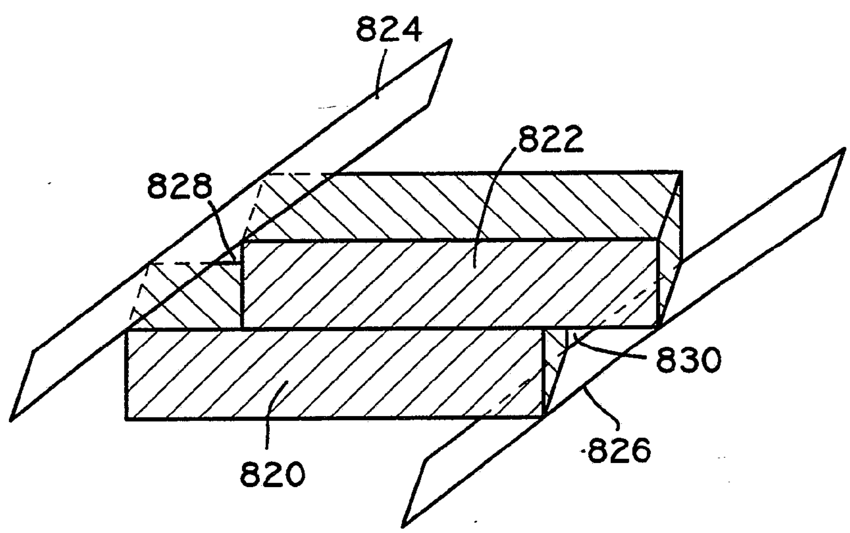


FIG. 60a

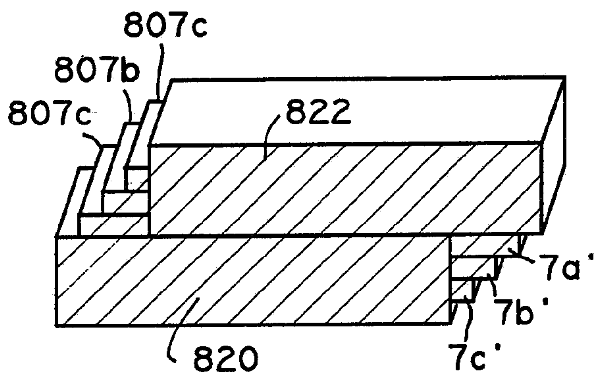


FIG. 60b

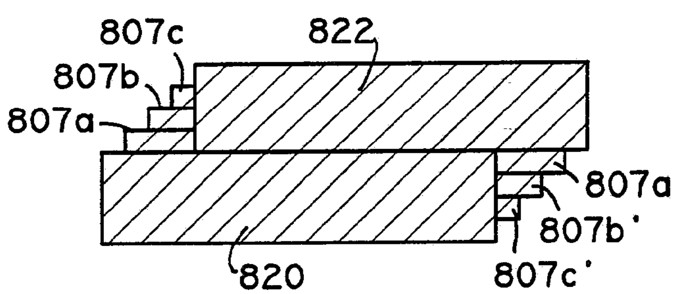


FIG. 60c

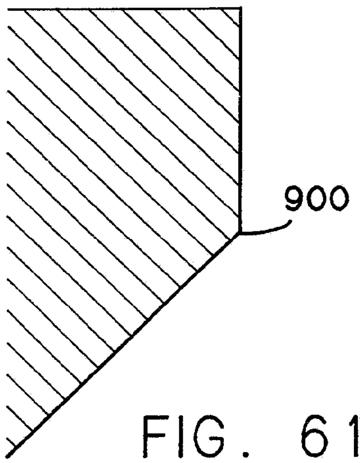


FIG. 61a

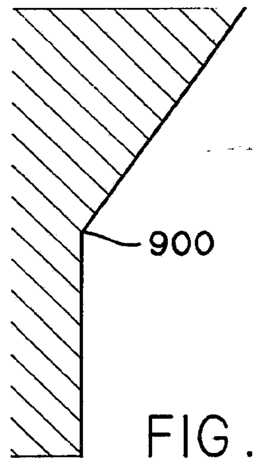


FIG. 61b

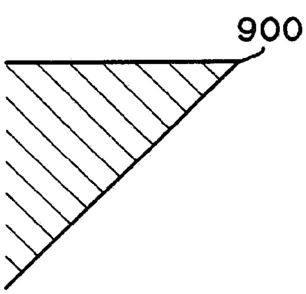


FIG. 61c

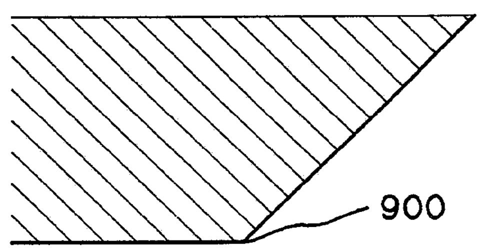


FIG. 61d

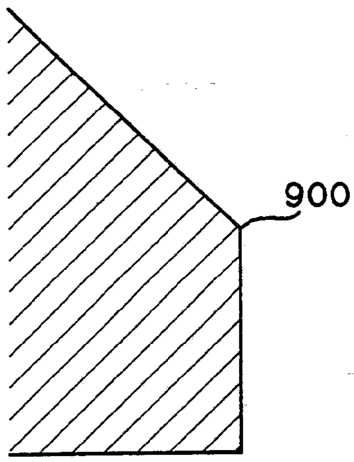


FIG. 61e

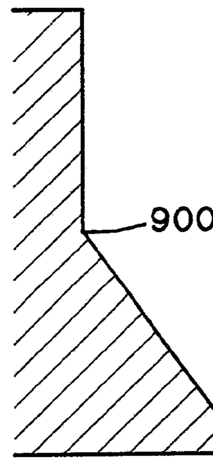


FIG. 61f

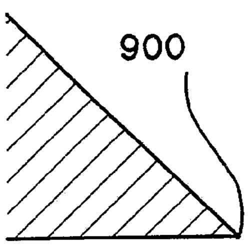


FIG. 61g

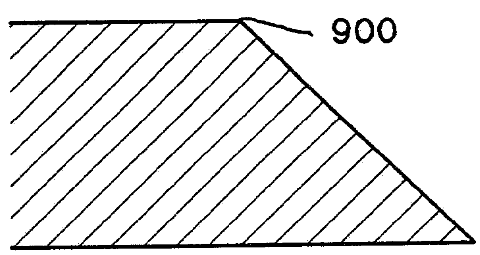


FIG. 61h

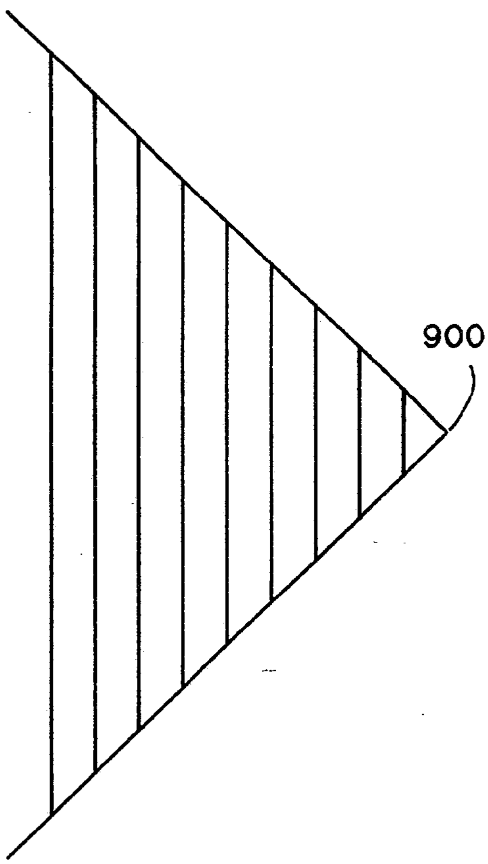


FIG. 61i

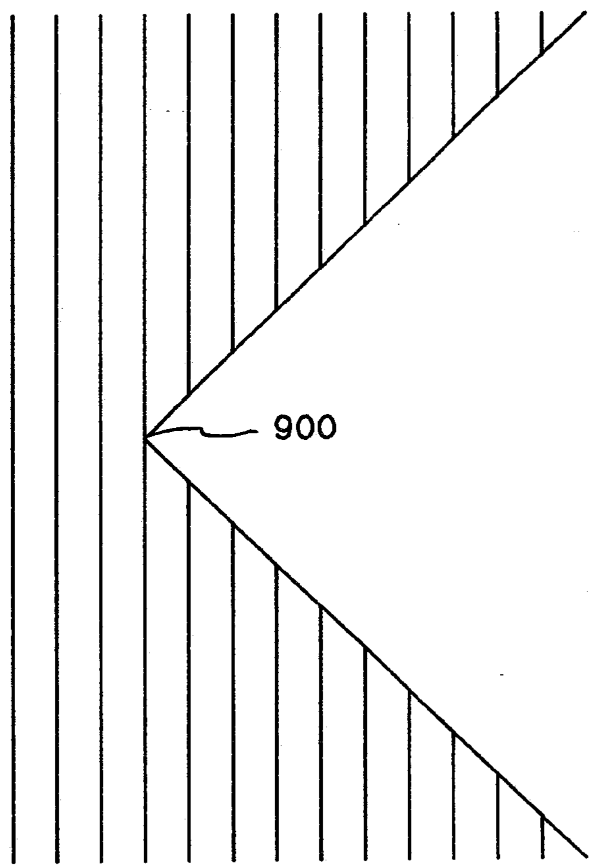


FIG. 61j

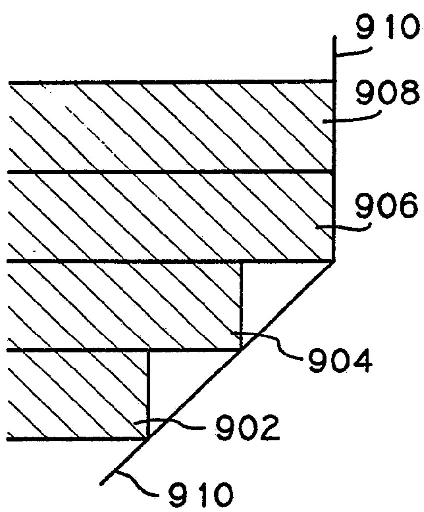


FIG. 62a

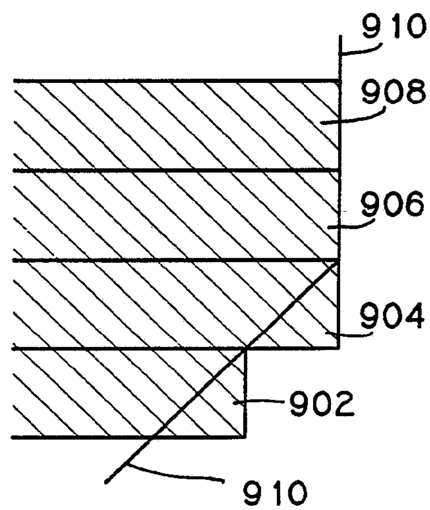


FIG. 62c

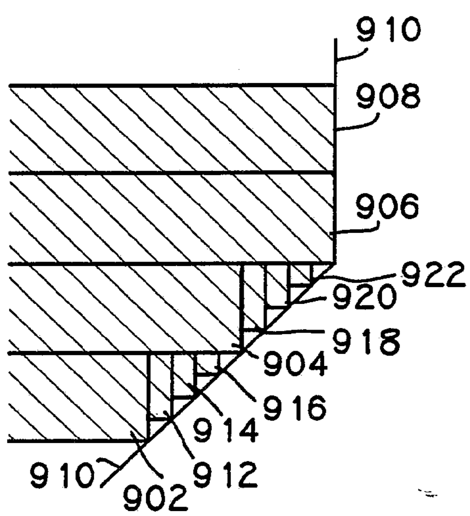


FIG. 62b

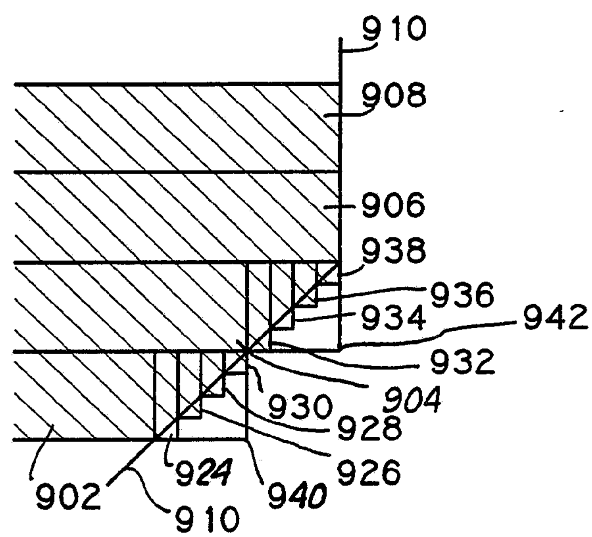


FIG. 62d

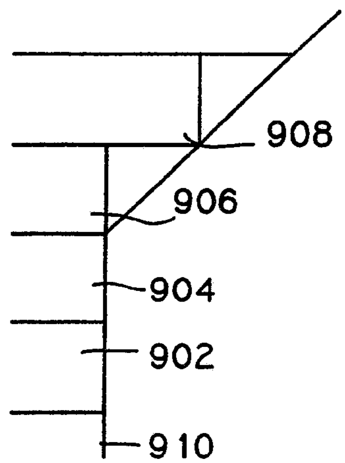


FIG. 63a

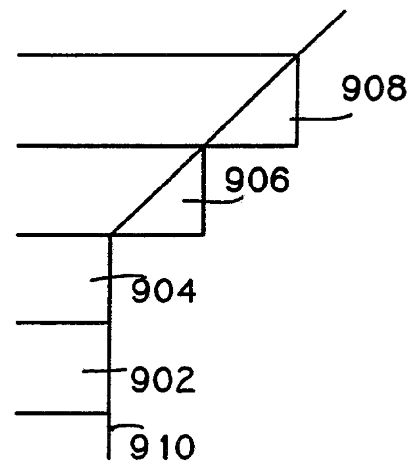


FIG. 63c

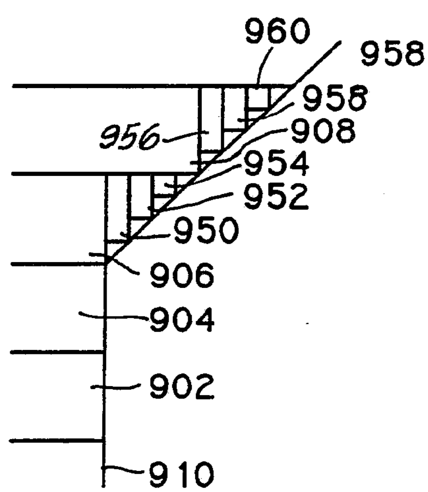


FIG. 63b

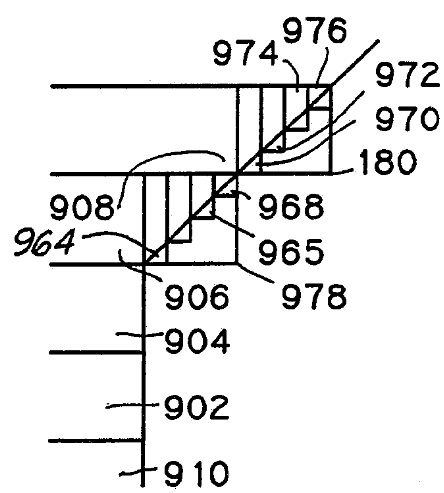


FIG. 63d

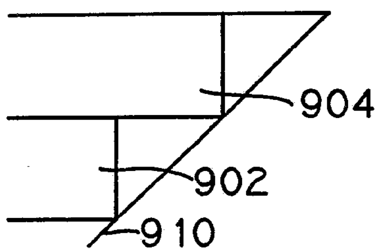


FIG. 64a

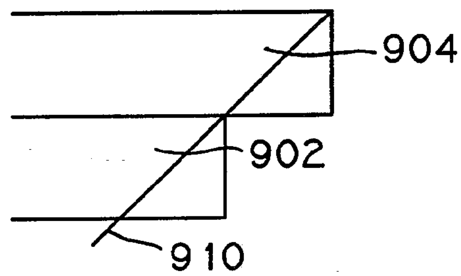


FIG. 64c

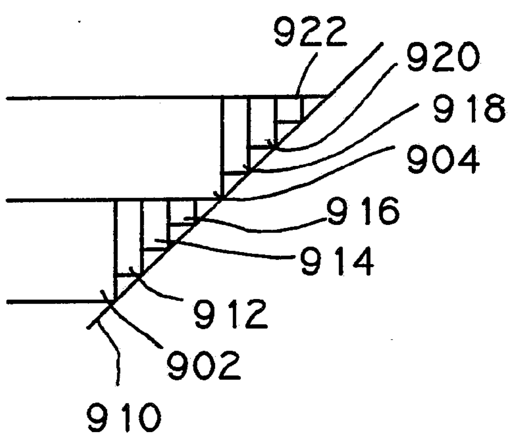


FIG. 64b

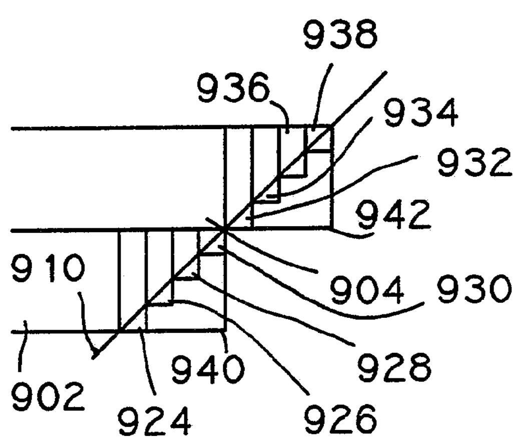


FIG. 64d

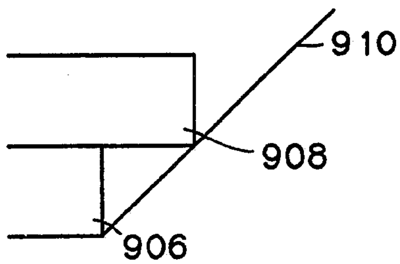


FIG. 65a

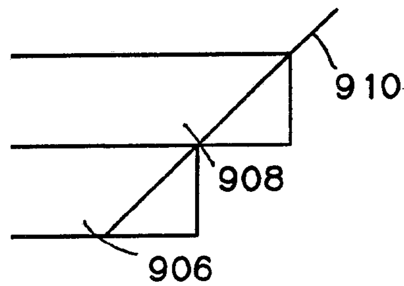


FIG. 65c

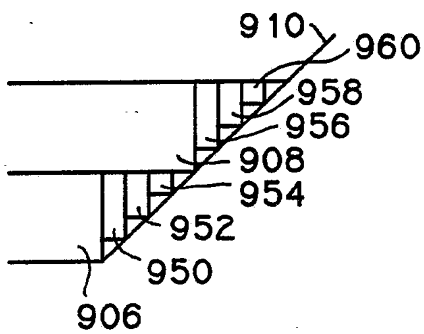


FIG. 65b

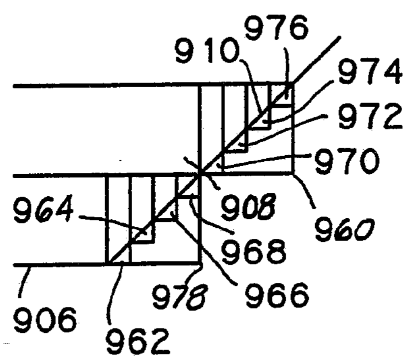


FIG. 65d

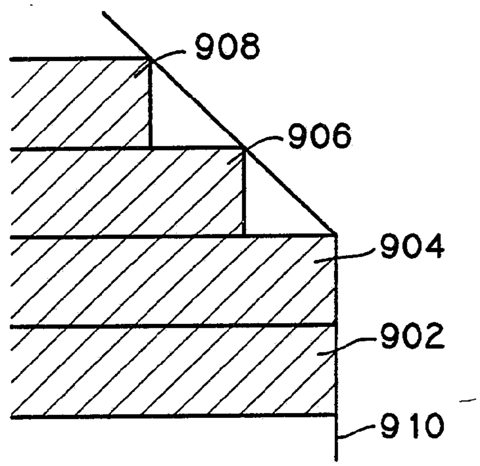


FIG. 66a

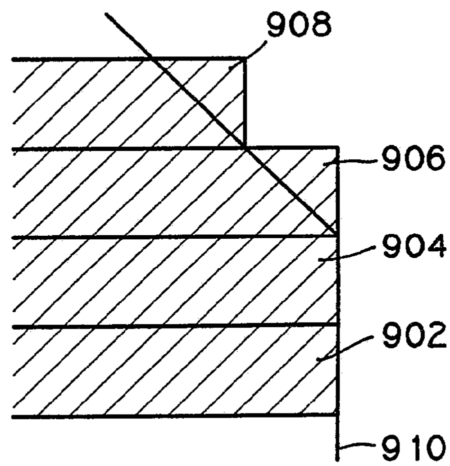


FIG. 66b

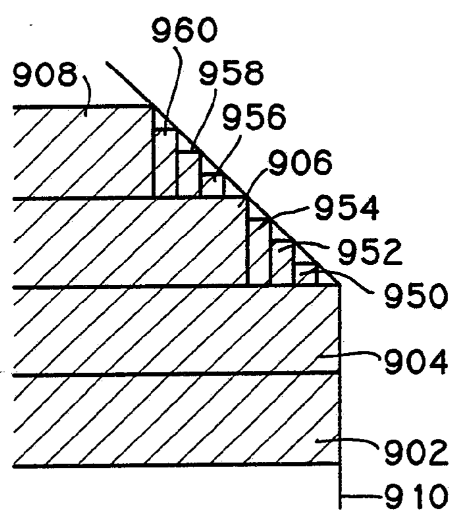


FIG. 66c

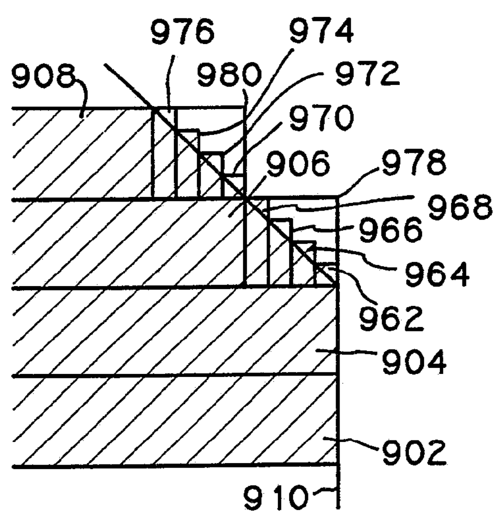


FIG. 66d

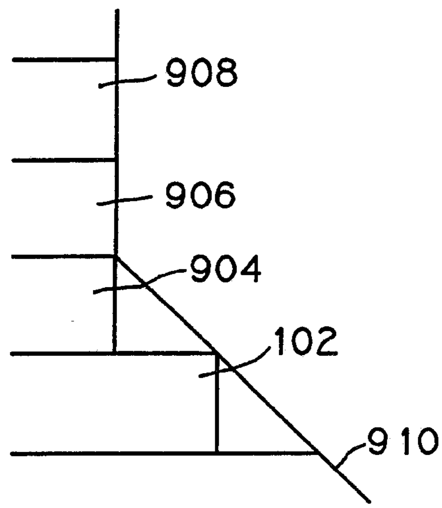


FIG. 67a

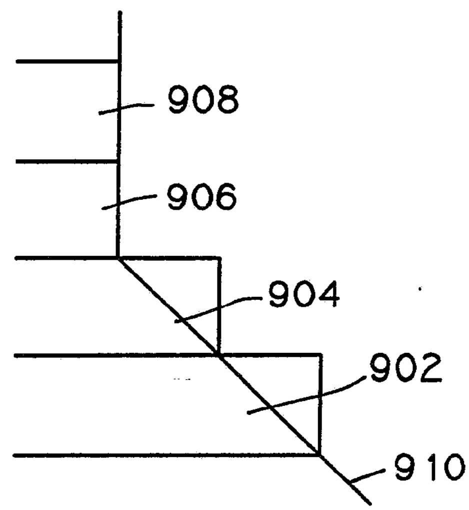


FIG. 67c

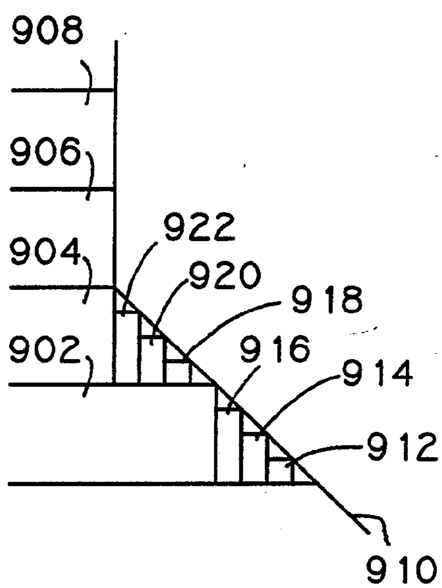


FIG. 67b

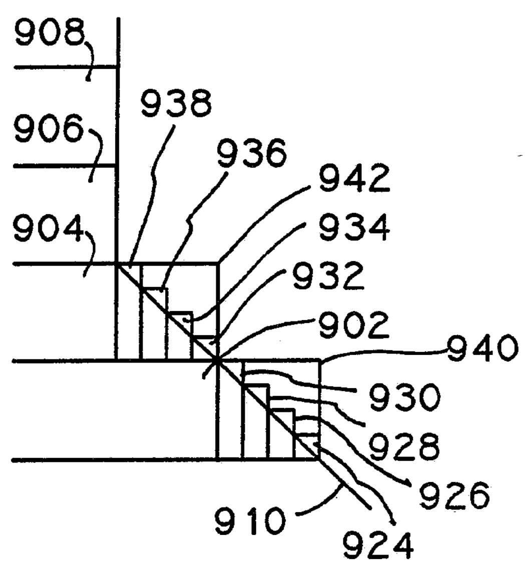


FIG. 67d

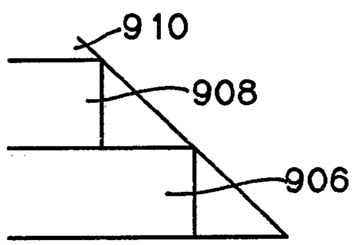


FIG. 68a

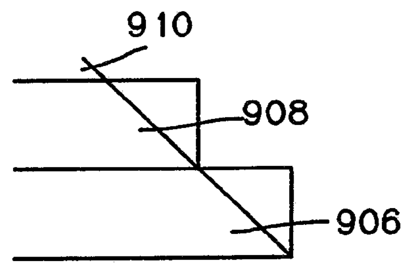


FIG. 68c

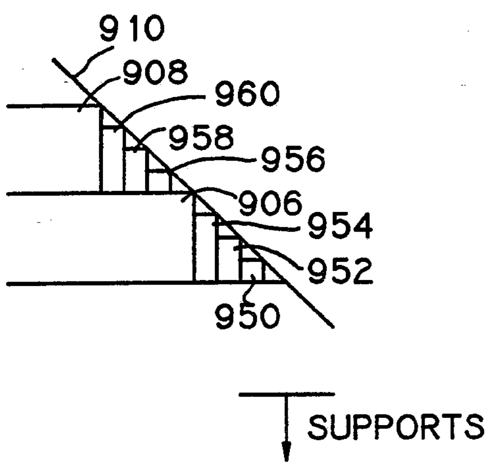


FIG. 68b

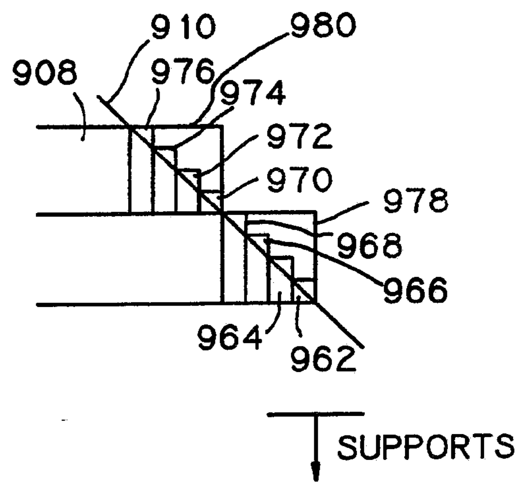


FIG. 68d

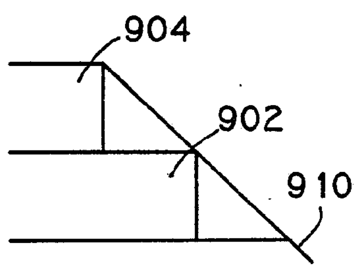


FIG. 69a

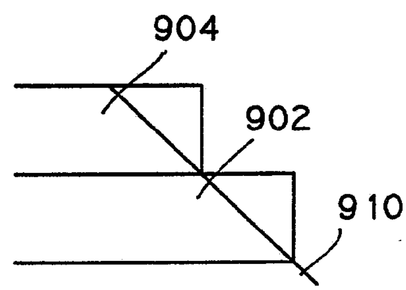


FIG. 69c

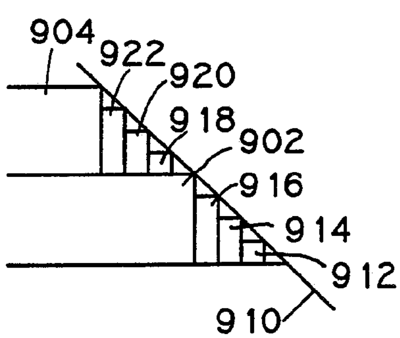


FIG. 69b

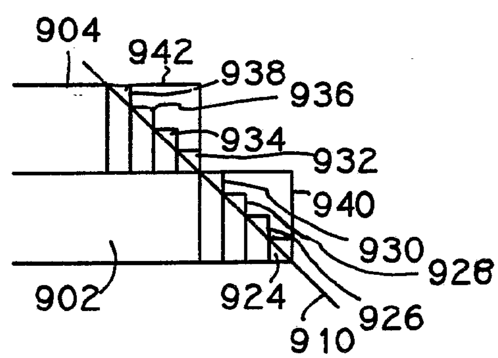


FIG. 69d

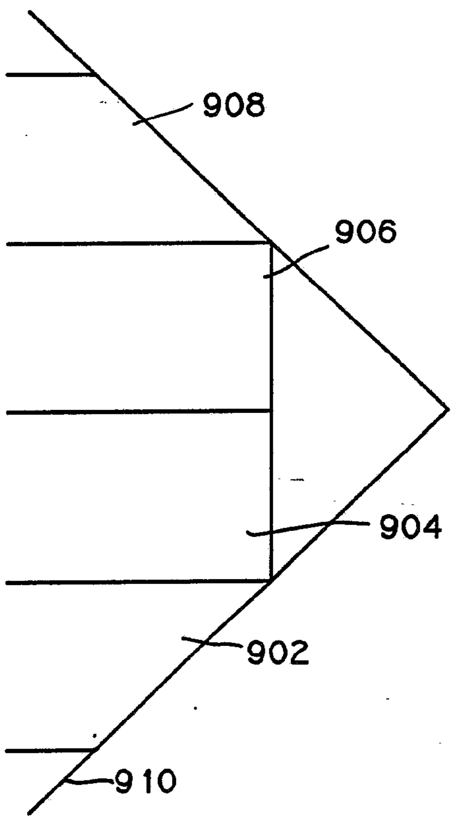


FIG. 70a

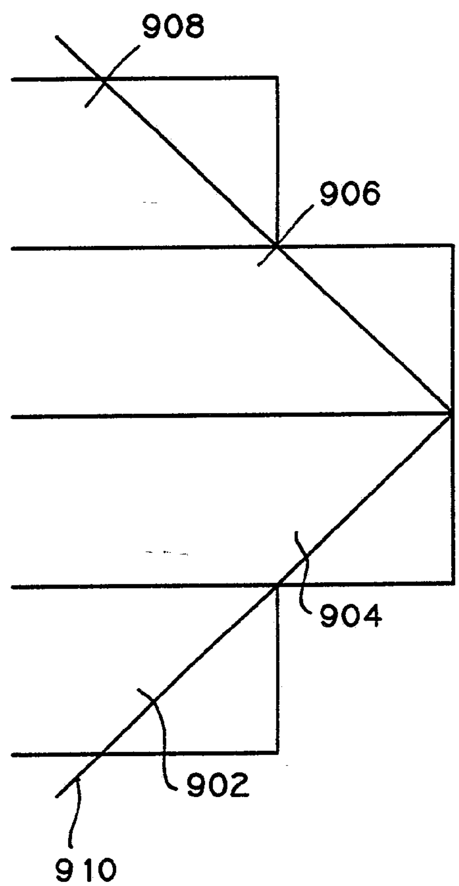


FIG. 70c

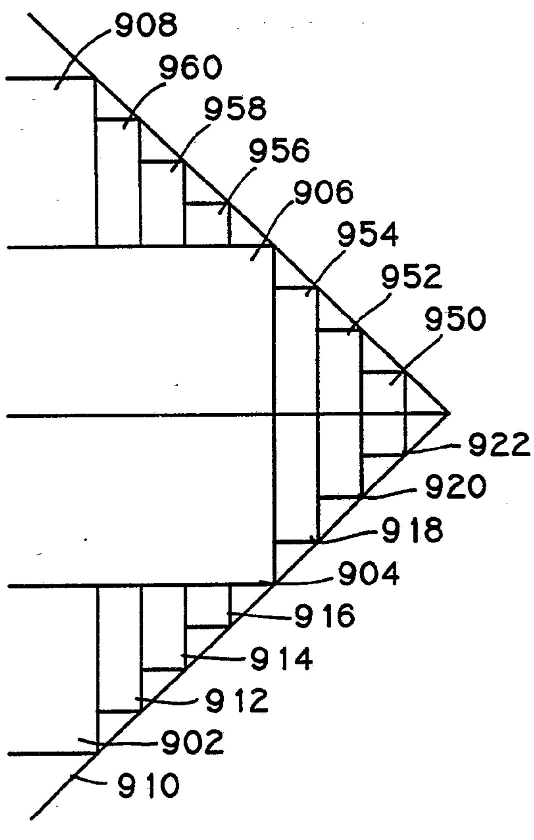


FIG. 70b

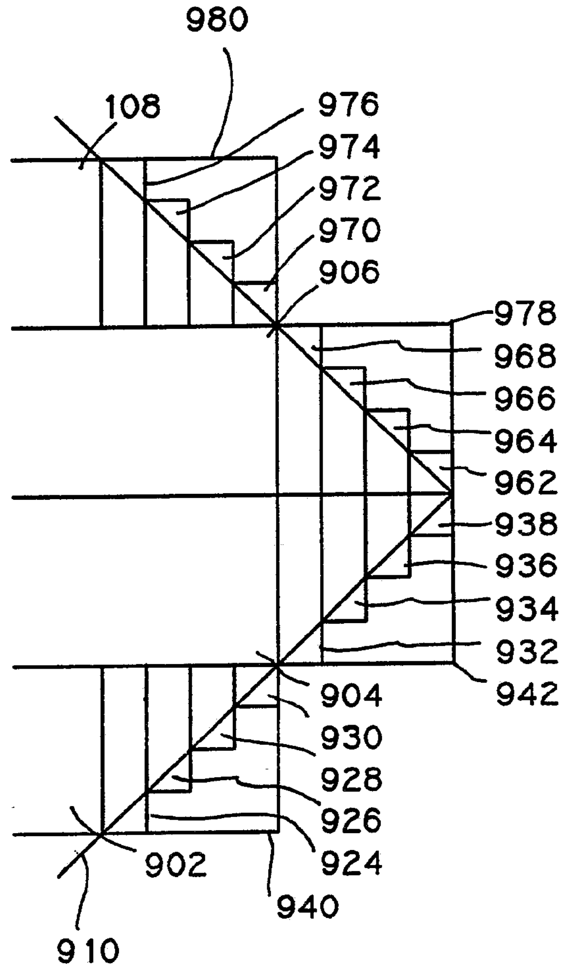


FIG. 70d

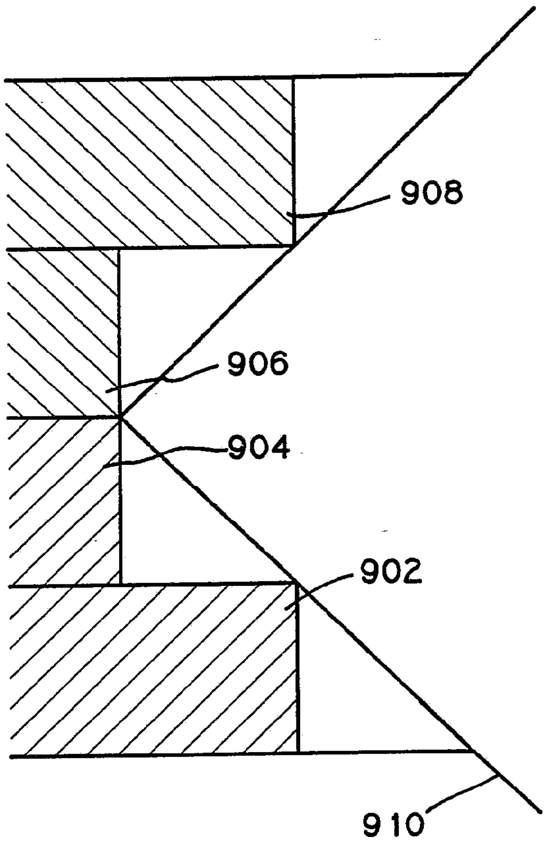


FIG. 71a

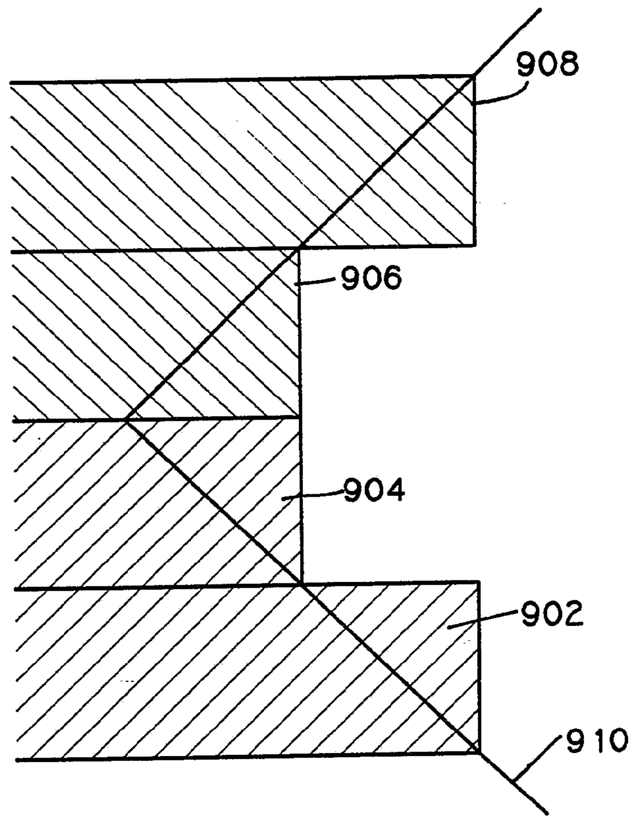


FIG. 71c

109/115

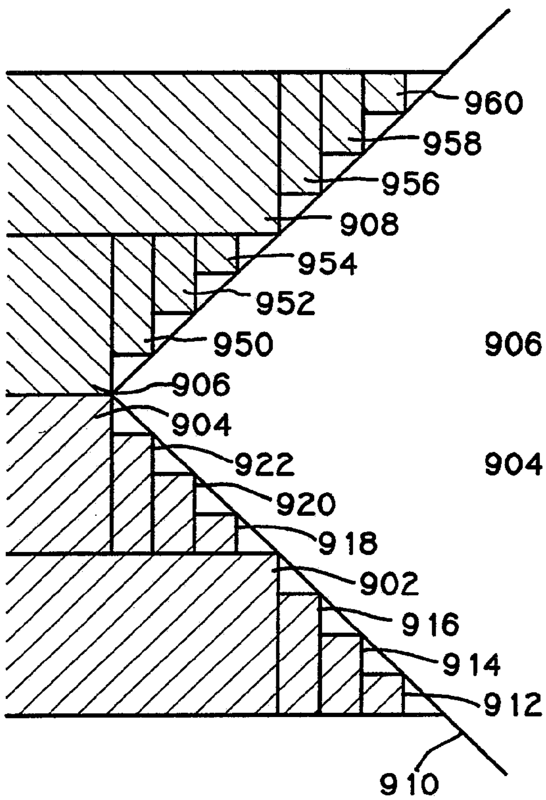


FIG. 71b

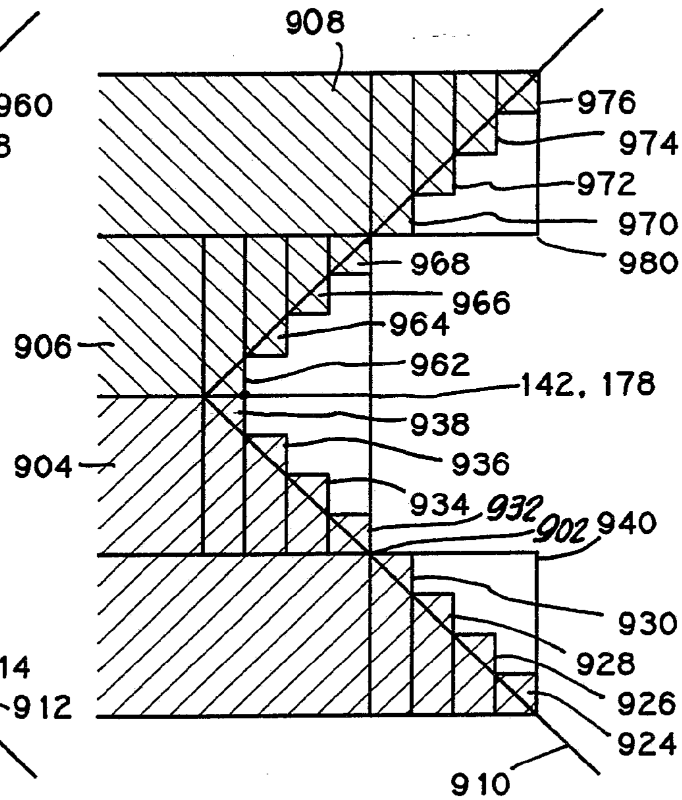
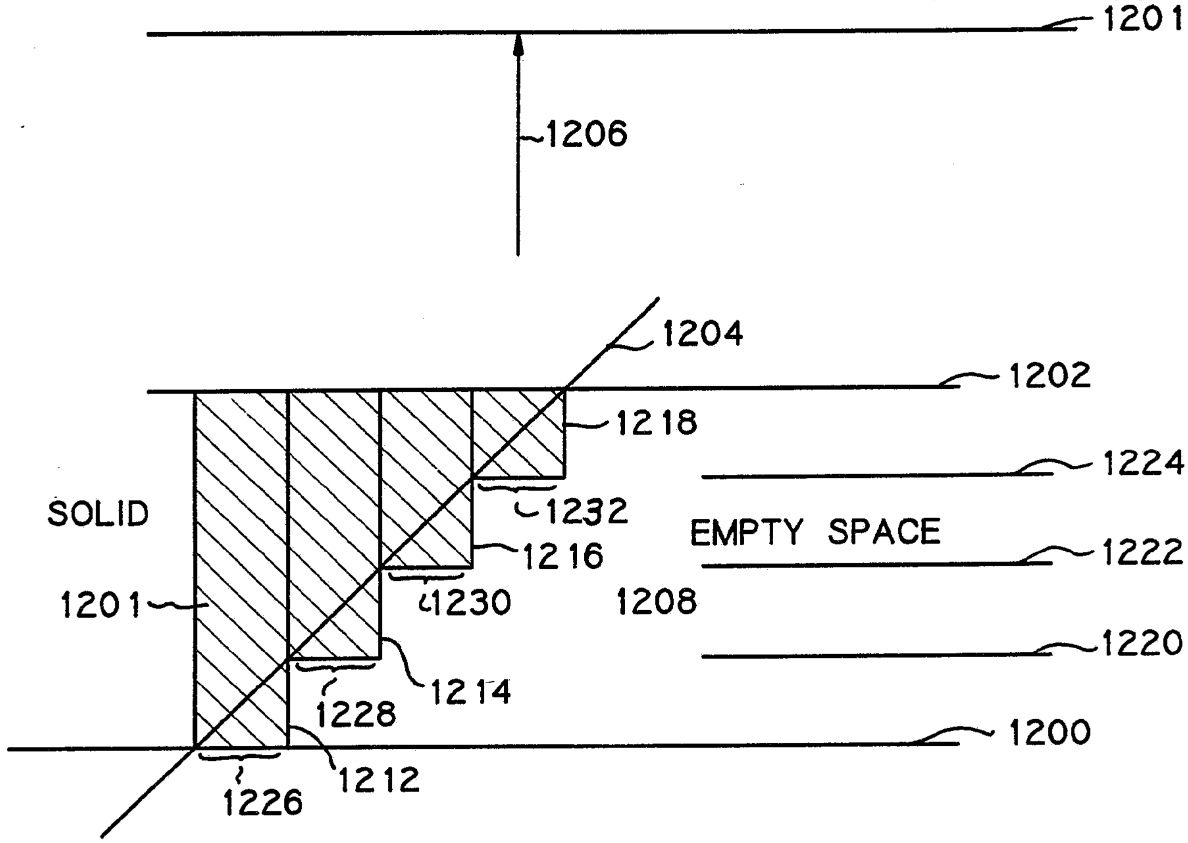


FIG. 71d


1201
1206
1204
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1218
1224
SOLID
1232
EMPTY SPACE
1216
1222
1201
1230
1208
1220
1228
1214
1200
1226
1212

FIG. 72

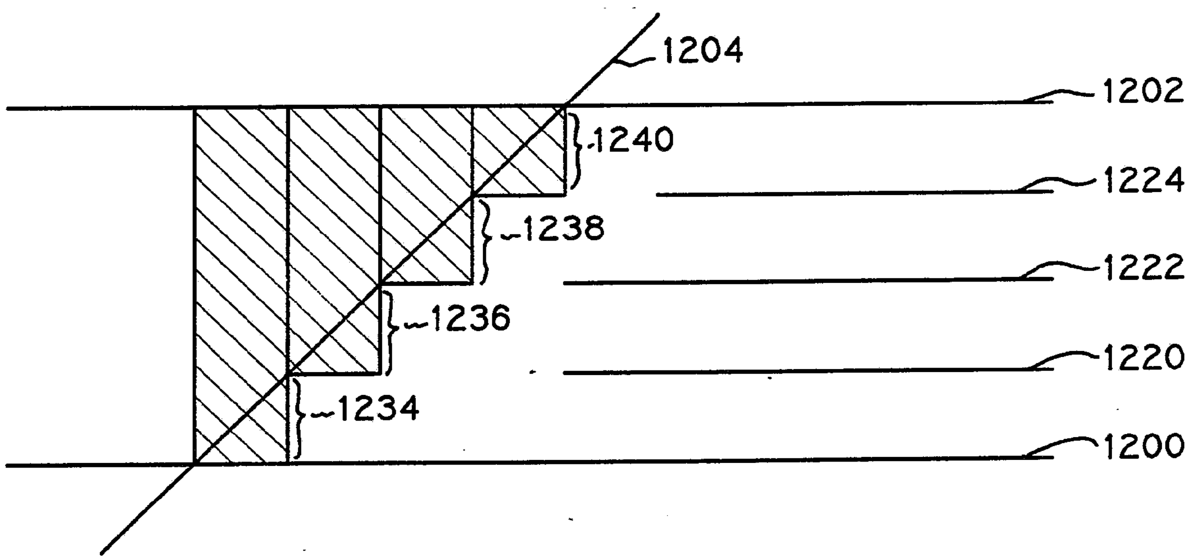
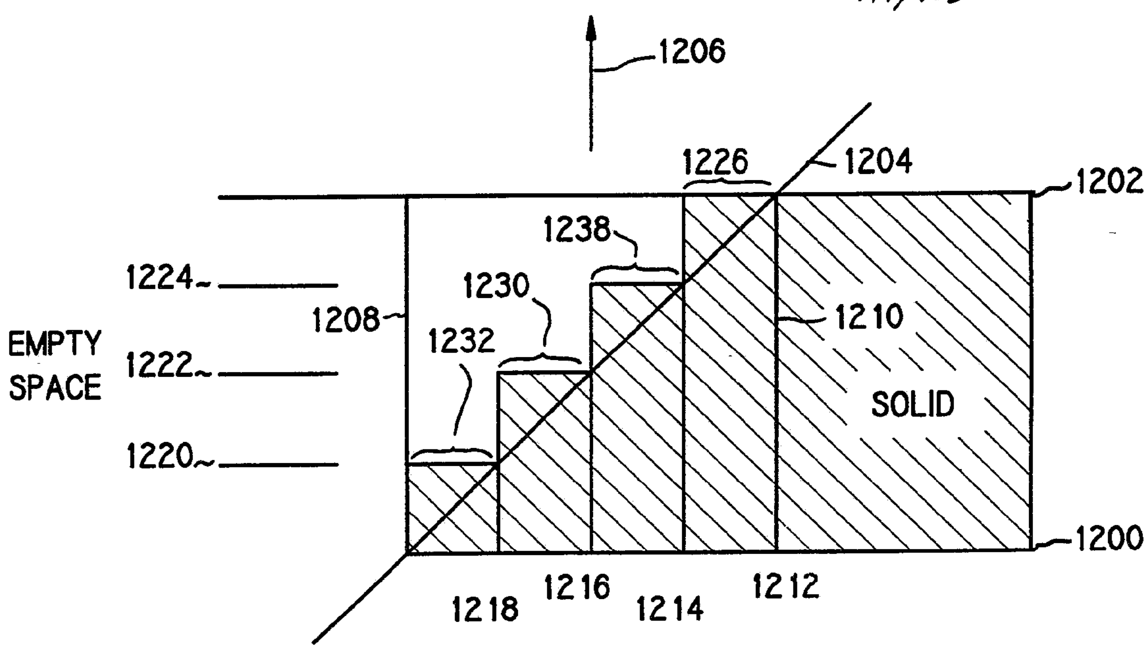

1204
1202
1240
1224
1238
1222
1236
1220
1234
1200

FIG. 73


1206
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1204
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EMPTY SPACE
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FIG. 74

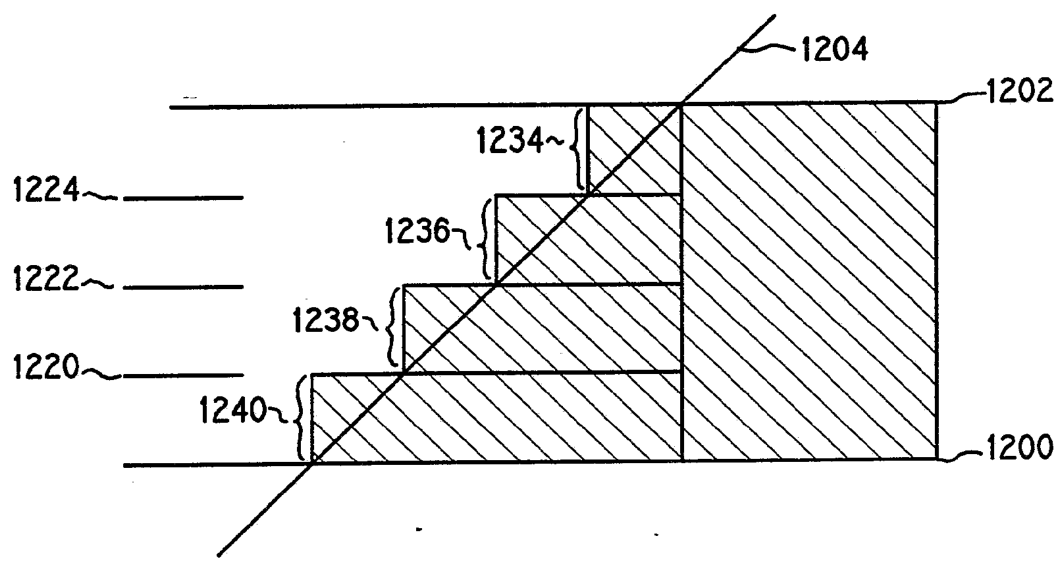
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FIG. 75

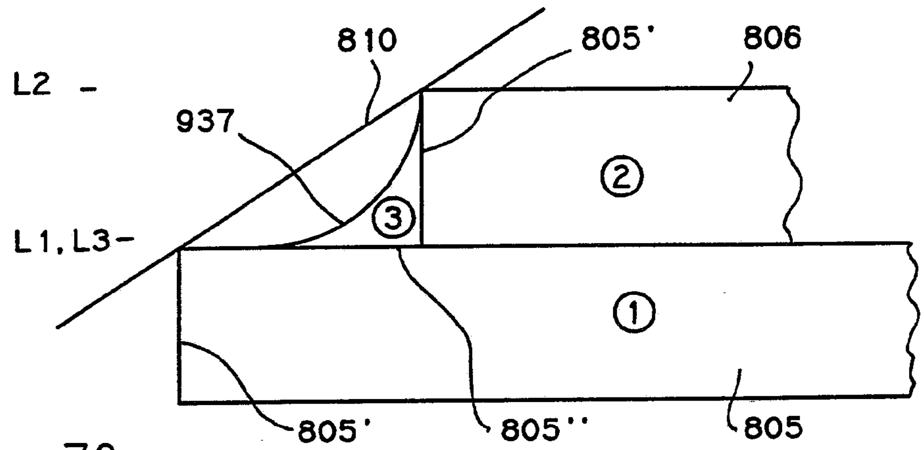

FIG. 76a

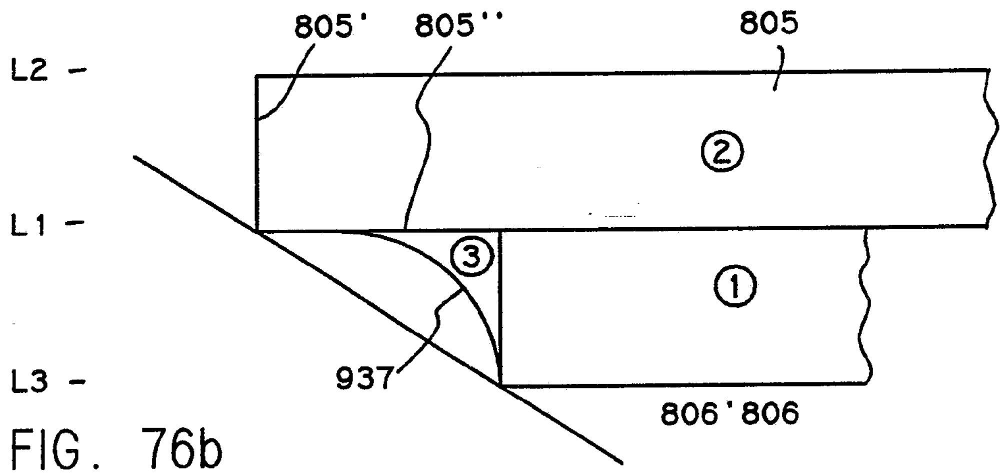

FIG. 76b

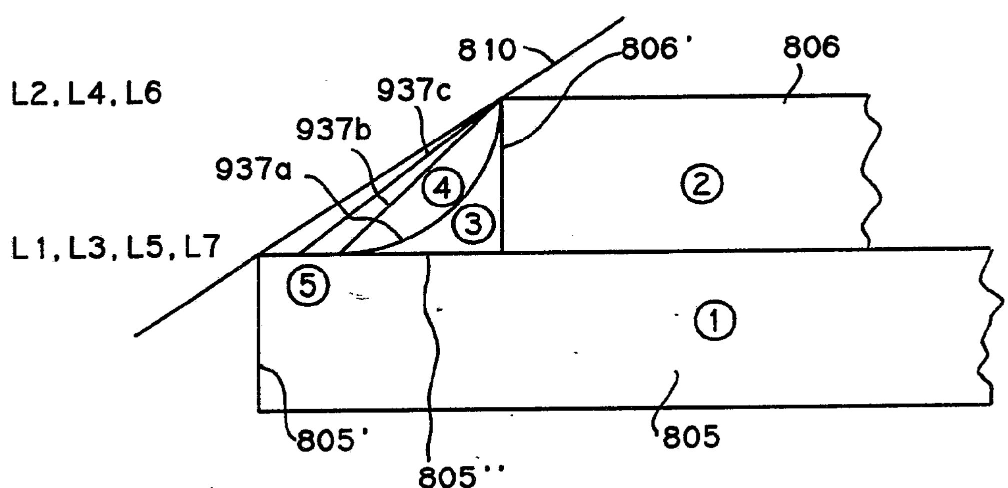

FIG. 76c

"IN-SITU SURFACE FINISHING BY "MENISCUS RAMP" METHOD

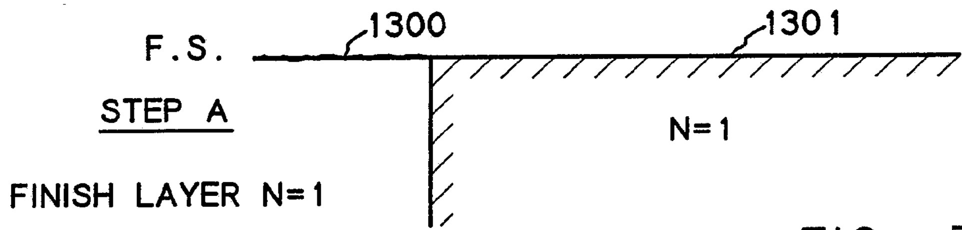

FIG. 77a

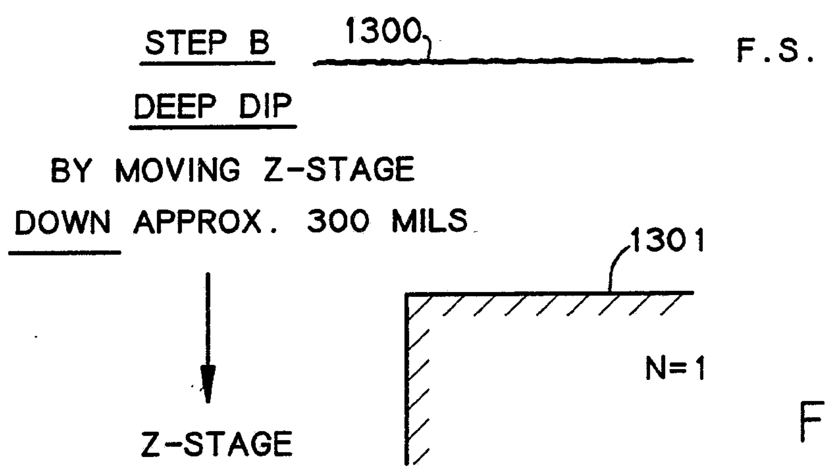

FIG. 77b

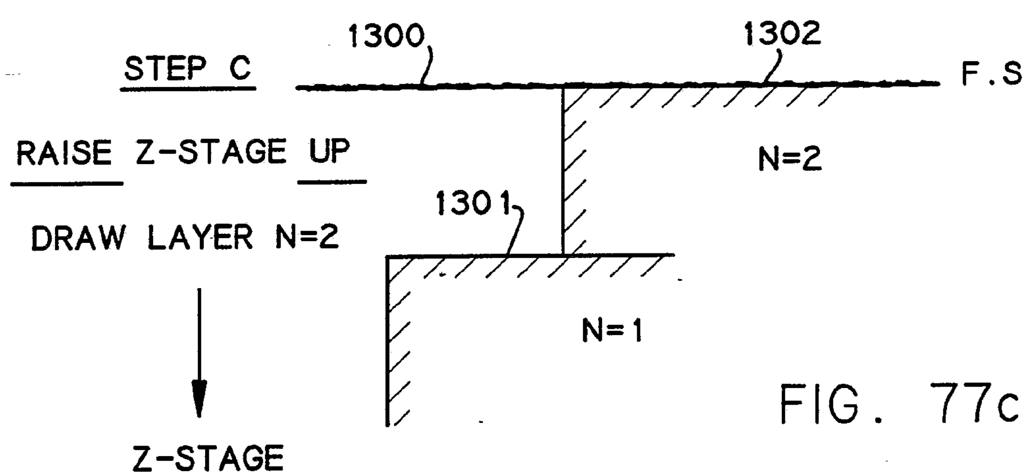

FIG. 77c

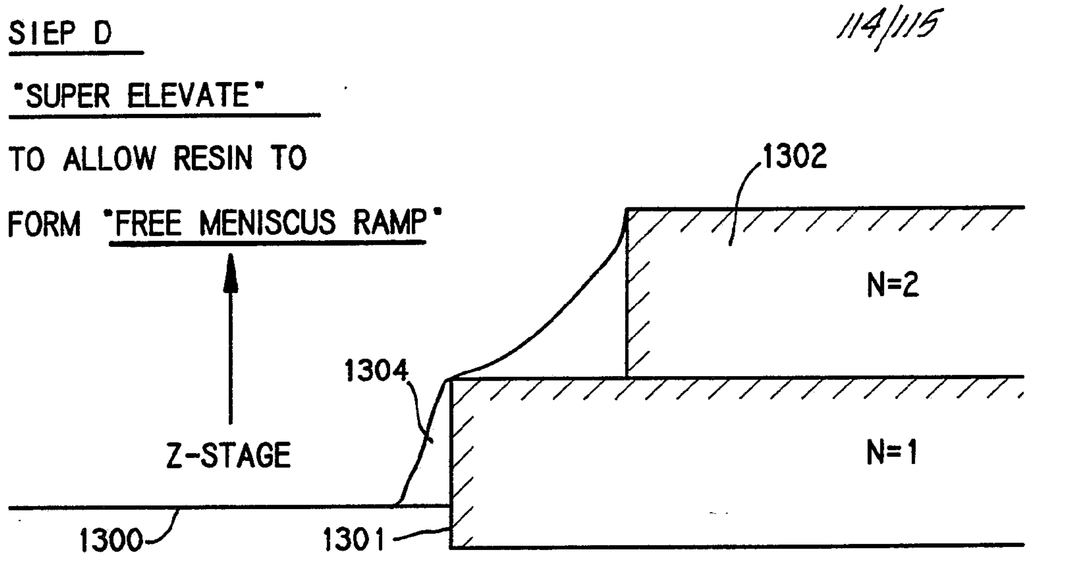

FIG. 77d

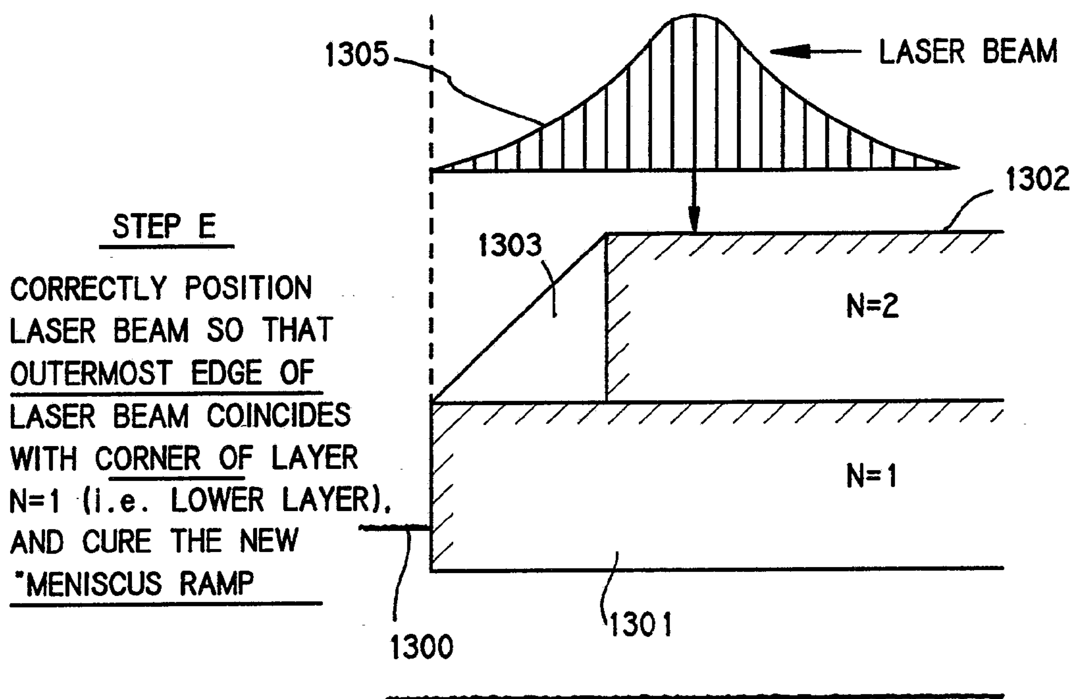

FIG. 77e

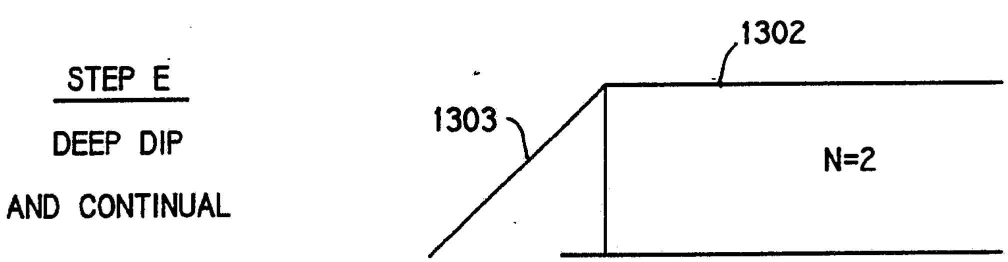

FIG. 77f

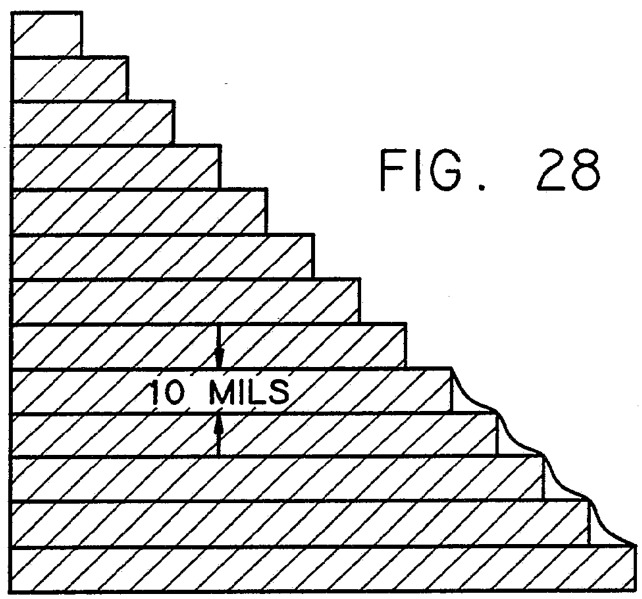

FIG. 28

INTERNATIONAL SEARCH REPORT

International Application No. PCT/US91/08110

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [6]

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC(5): G06F 15/46
U.S. CL.: 364/468,474.24; 395/119

II. FIELDS SEARCHED

Minimum Documentation Searched [7]

Classification System	Classification Symbols
U. S.	364/468,474.24 395/119-127,155,161 264/22; 425/174.4

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [9]

Category *	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No [13]
A	US, A, 4,575,330 (HULL) 11 MARCH 1986 See the entire document.	1-18
A	US, A, 4,665,492 (MASTERS) 12 MAY 1987 See the entire document.	1-18
A	US, A, 4,961,154 (POMERANTZ) 2 OCTOBER 1990 See the entire document.	1-18
A,P	US, A, 5,031,120 (POMERANTZ) 9 JULY 1991 See the entire document.	1-18

* Special categories of cited documents: [10]

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
21 JANUARY 1992	04 MAR 1992
International Searching Authority	**Signature of Authorized Officer**
ISA/US	JOSEPH E. RUGGIERO

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CORRECTED VERSION *

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606,191	30 October 1990 (30.10.90)	US
606,802	30 October 1990 (30.10.90)	US
607,042	31 October 1990 (31.10.90)	US

(71) Applicant: 3D SYSTEMS, INC. [US/US]; 26081 Avenue Hall, Valencia, CA 91355 (US).

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(74) Agents: OHRINER, Kenneth, H. et al.; Lyon & Lyon, 611 West 6th Street - 34th Floor, Los Angeles, CA 90017 (US).

(81) Designated States: AT (European patent), BE (European patent), CA, CH (European patent), DE (European patent), DK (European patent), ES (European patent), FR (European patent), GB (European patent), GR (European patent), IT (European patent), JP, KR, LU (European patent), NL (European patent), SE (European patent).

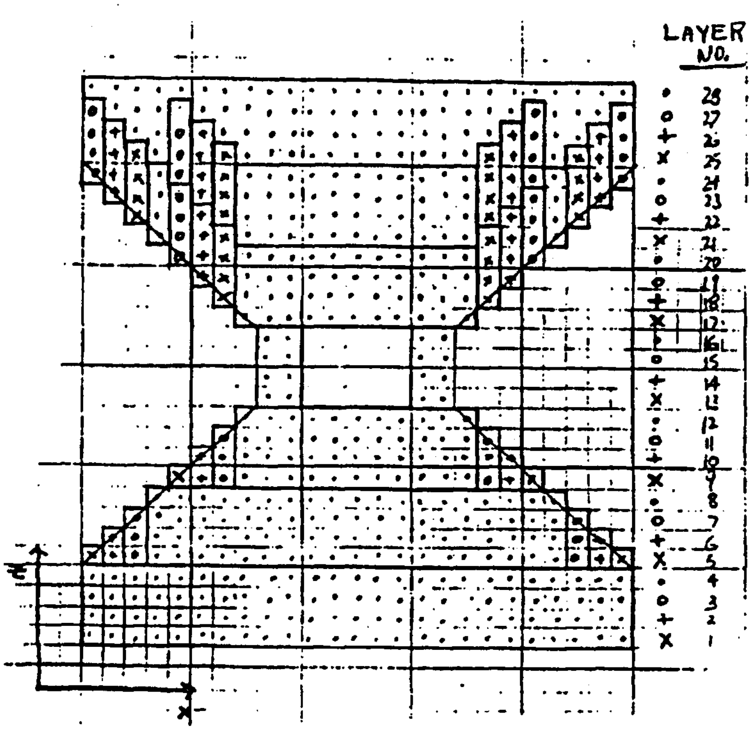
Published

With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: LAYER COMPARISON TECHNIQUES IN STEREOLITHOGRAPHY

(57) Abstract

A method of and apparatus for slicing a three-dimensional object representation into a plurality of layer representations. The layer representations are subsequently used to form the object layer-by-layer from a solidifiable material by stereolithography (711). If not already provided in the object representation, a plurality of layer boundary representations are first formed, and then the boolean difference (17), of successive layer boundary representations are computed to derive boundaries of up and down-facing regions, enabling different cure parameters to be specified for these different regions. In another method, the depth of the curable material within the objet underlying a selected area element is determined and compared to the depht to the minimum solidification depth of the material. The area element is exposed to solidifying synergistic stimulation only if the depth of the material equals or exceeds the minimum solidification depth. A next layer is created over the first layer without curing the first layer, if the depth is less than the minimum solidification depth. Another method and apparatus (714) eliminates or substantially reduces curling effects in stereolithographically formed objects. Synergistic stimulation is applied to a curable material to form a three-dimensional object through the build up of successive layers.



* (Referred to in PCT Gazette No. 19/1992, Section II)

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STEP D

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TO ALLOW RESIN TO

FORM "FREE MENISCUS RAMP"

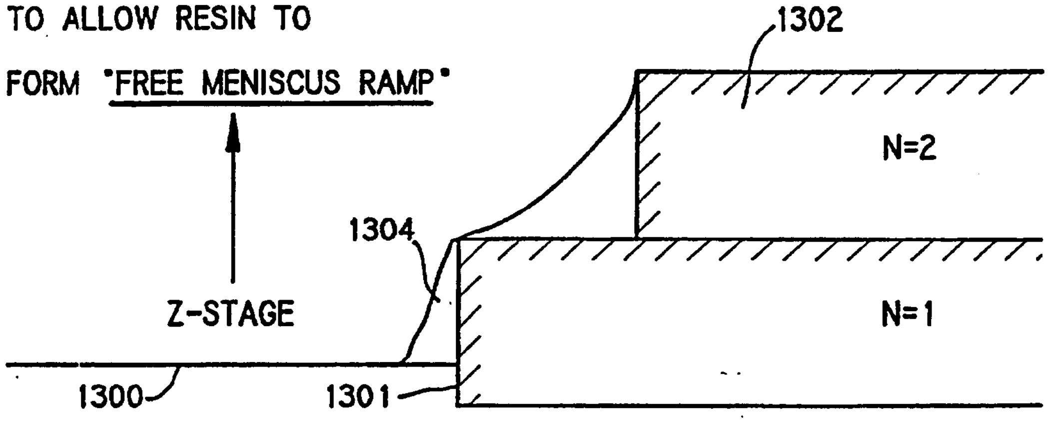
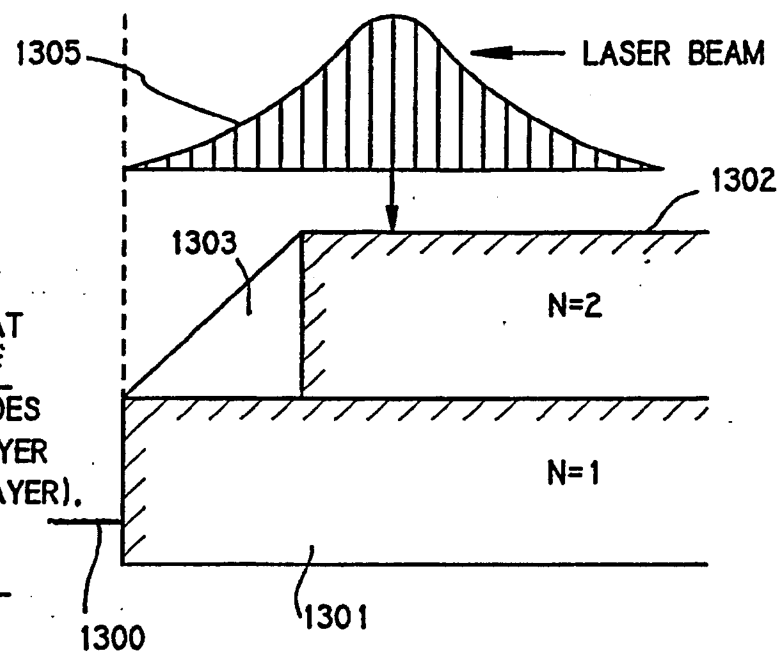


FIG. 77d



STEP E

CORRECTLY POSITION LASER BEAM SO THAT OUTERMOST EDGE OF LASER BEAM COINCIDES WITH CORNER OF LAYER N=1 (I.e. LOWER LAYER), AND CURE THE NEW "MENISCUS RAMP

FIG. 77e

STEP E

DEEP DIP

AND CONTINUAL

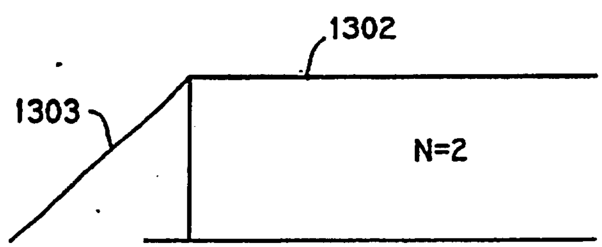


FIG. 77f